Chapter 4
Advanced Transport Systems: Technologies and Environment

4.1 Introduction

This chapter deals with the performances of advanced passenger cars, large advanced container ships, and LH_2 (Liquid Hydrogen)-fuelled commercial air transportation. The prime objective is to show the potential effects of such advanced technologies on the environment in terms of energy/fuel consumption and related emissions of GHG (Green House Gases).

Man-made GHG emissions, particularly those from using nonrenewable energy sources, have become an increasing burden on the industry, society, and politics all around the world. This is because these emissions and particularly their CO_2 component (Carbon Dioxide) are perceived to remain in the atmosphere for prolonged periods of time (presumably hundreds of years) and are proven to contribute to global warming and consequent climate change (Archer 2008). In order to mitigate or even diminish these impacts, both national and international policy makers, industrial organizations, and associations have undertaken a range of different measures. For example, in Europe, the EU (European Union) 27 Member States have fully institutionalized the problem by introducing national and international legislations and conventions, in addition to setting up specific targets for the absolute and relative reduction in emissions of particular GHG. These targets are expected to be achieved by a range of advanced technical/technological and operational improvements and by monitoring and reporting developments throughout particular air polluting sectors of the economy and society (EEA 2010). The most recent evidence indicates that some results have already been achieved: the total emissions of GHG have decreased by about 20 % over the 1990–2009 period, from 5,589 in 1990 to 4,674.5 million tons of CO_{2e} (Carbon Dioxide equivalents) in 2009 (CO_{2e} include CO (Carbon Oxide), CO_2 (Carbon Dioxide), SO_4 (Sulfur Oxides), NO_x (Nitrogen Oxides), H_2O (water vapor), and particles). However, at the same time, the share of transport sector in the total emissions of CO_{2e} has increased from about 17 % in 1990 to about 26 % in 2009, which is an equivalent of about 951 and 1,225 million tons of CO_{2e}, respectively (EC 2010a, b).

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In particular, road transport and specifically passenger cars have substantially contributed to the above-mentioned increase in the total emissions of GHG, as their share in the total volumes of vehicle-kilometers by road amounted to about 73 % during the 2005–2009 period. In absolute terms, these total volumes have increased from about 2,433 million in 1995 to about 3,061 million vehicle-kilometers in 2009 (EC 2010a, b; EEA 2010).

The world's economic development and international trade have been strongly supported by maritime transport whose freight ship fleet has been permanently growing aiming to satisfy growing demand. The fleet consists of different types of ships such as bulk, container, general cargo ships, oil tankers, and other ships. A substantial fast-growing part of this fleet consists of large advanced container ships. These and other freight ships use diesel fuel, which, in combination with higher demand, has resulted in an increase of GHG emissions. Consequently, maritime transport, which is currently not part of the Kyoto Protocol, accounts for about 3.3 % of the global man-made GHG emissions with the share of its international part in this total of about 2.2 %. Unless global policies aimed at controlling these emissions are put into place, they will likely increase by about 200–300 % by 2050 as compared to the figures in 2009, mainly driven by the expected continued growth in international trade. For example, in the EU-27 Member States, international maritime transport is the second largest source of GHG emissions by the transport sector. In 2007, international maritime transport emitted about 176 million tons of CO_{2e} mainly on account of transportation of 3,934 million tons of freight/goods. As compared to the emitted volumes in 2002, this represents an overall increase of about 18 % (EEA 2012; UNCDAT 2012).

In order to prevent the above-mentioned negative developments in the EU27 and the rest of the world, the shipping industry has undertaken a variety of technical/technological and operational measures to improve the sector's efficiency. The aim is two-fold: to reduce operational costs on the one hand and improve energy efficiency by reducing fuel consumption and related emissions of GHG on the other. Particularly relevant for large advanced container ships, the former measures include building fuel-efficient and environmentally friendly ships and promoting a switch to alternative/cleaner fuels. The latter measures imply adopting slow steaming. In addition, the international community, including the IMO (International Maritime Organization), has undertaken some measures to influence the energy efficiency of all, including large advanced container ships, aiming at reducing the rates of emissions of GHG (CO_2/ton-mile) below the current level. By combining the technical/technological and operational improvements, it seems possible to reduce these emissions by about 15–20 % by 2020 and by about 30 % by 2025 and beyond (IMO 2011; MEPC 2012).

The commercial APT (Air Passenger Transport) system mainly driven by economic/GDP (Gross Domestic Product) growth has grown over the past decades contributing to both globalization of the world's and national economies and overall social welfare on the one hand, and increasing energy consumption of nonrenewable sources (crude oil), related emissions of GHG and local noise, on the other. For example, the number of RPK (Revenue Passenger Kilometers) has increased from

0.5 trillion in 1971 to about 4.25 trillion in 2006. Some long-term forecasts by international air transport organizations (IATA, ICAO, ACI), and in particular by the two main manufacturers of commercial aircraft Boeing and Airbus, predict the rather stable long-term growth of RPKs at an average annual rate of 4.6–5 % over the next 20 years, mainly on account of average annual GDP growth of about 3.5 %. This will increase the total volumes of the world's traffic to about 10.545 trillion RPKs (Airbus 2006) and 11.4 trillion RPKs (Boeing 2007) by 2025/26. At the same time, the number of passengers is predicted to rise at an annual rate of 4.5 %, which will result in a total of about 6.8 billion in 2025/26 (Boeing 2007). The above-mentioned growth of air traffic will require an increasing number of aircraft, from the current 18,230 (of which 16,250 are passenger aircraft) in 2006 to about 36,420 (of which 32,440 will be passenger aircraft) in 2025/26 (Boeing 2007). Since all these aircraft are assumed to use conventional jet fuel as a derivative of crude oil, the total fuel consumption and related emissions of GHG will continue to increase, contributing to global warming and climate change (Airbus 2006; Boeing 2007; IPCC 1999). Some estimates indicate that the air transport sector emitted about 513 $MtCO_2$ in 1992. This is expected to increase to about 1,468 $MtCO_2$ in 2050. The latter quantity will likely continue to account for between 3–5.5 % of the total man-made emissions of CO_2 (ICAO 2008; IPCC 1999, 2001).

4.2 Advanced Passenger Cars

1901	Electric cars-taxi cabs appear in New York (U.S.)
1911	The first gasoline–electric hybrid car is released by the Woods Motor Vehicle Company of Chicago (U.S.)
1997	The world's first mass-produced Toyota Prius electric–gasoline hybrid car is released (Japan)
1999	The first Honda Insight hybrid car since the little-known Woods hybrid of 1917 is sold in North America; sales of the hybrid Toyota Prius substantially increase; many car makers release hybrid models and several began to produce new electric car prototypes (U.S.)
2008	The first Tesla Roadster all-electric car developed by Tesla Motors in serial production is sold to customers (U.S.)
2009/2010	The Mitsubishi i-MiEV electric car is launched (Japan)

4.2.1 Definition, Development, and Use

At present, the majority of passenger cars use petrol and diesel fuel as a derivative of crude oil and natural gas, the burning of which contributes to the above-mentioned emissions of GHG. Consequently, under the assumption that volumes of passenger

car use will continue to grow, that the reserves of crude oil and natural gas will become depleted and eventually vanish, and that the emissions of GHG will remain in the atmosphere for prolonged periods, thus indicating their continuous increase in cumulative amounts, various improvements of existing and developing advanced passenger car technologies have been undertaken. Among other, they aim, together with other operational, social, and policy measures, to mitigate the above-mentioned emissions of GHG over the medium- to long-term future (IPTS 2008).

4.2.2 Analysis and Modeling Performances

4.2.2.1 Background

Both existing conventional and advanced forthcoming passenger car technologies are characterized by their technical/technological, operational, economic, environmental, and social/policy performances. In the given context, the technical/technological performance mainly relates to the vehicle size (the number of seats, weight), and the engine type characterized by its volume/power and energy/fuel efficiency. The operational performances include the maximum and the most fuel/energy efficient speed. The economic performances include the purchase price and operational costs (fuel, maintenance). The environmental performances mainly include the emissions of GHG, which depend on the energy/fuel used. These could also include land use for operating—maneuvering and parking. The social/policy performances relate to noise, congestion, and general public acceptance.

4.2.2.2 Analyzing Performances

At present, the following passenger car technologies based on the type of energy/fuel use can be distinguished: conventional petrol/diesel/gas ICEVs (Internal Combustion Engine Vehicles), HYVs (Hybrid Vehicles), BEVs (Battery Electric Vehicles), HVs (Hydrogen Vehicles), and HFCVs (Hydrogen Fuel Cell Vehicles). The last three categories of cars, and particularly the latter two, are expected to more intensively penetrate the EU27 and other world markets over the forthcoming decades. However, this can only be expected if they are able to provide an equivalent overall convenience to their users—at least at the level provided by today's conventional ICEVs and/or if they become exclusive alternatives due to the depletion of reserves of crude oil, making more convenient ICE cars practically unusable.

ICEVs (Internal Combustion Engine Vehicles)

Conventional ICEVs (Internal Combustion Engine Vehicle(s)) are considered as relatively low energy/fuel efficient due to the fact that as a result of converting fuel into propulsion, most of the energy is emitted as heat. Typical petrol ICEVs

engines effectively use only 21 % of the fuel energy content to move the vehicle and their diesel ICE counterparts are efficient up to 25 %. This WTW (Well-to-Wheel) efficiency includes the energy consumed to produce and deliver fuel to the station (WTT (Well-to-Tank)) and the energy used to fill and consume it in the car (TTW (Tank-to-Wheel)) (Bodek and Heywood 2008).

Currently, in the EU (European Union)-27 Member States, conventional ICEVs are categorized into three categories depending on the engine volume: Small <1.4 l, Medium >1.4 and ≤2.0 l, and Big >2.0 l (l—liter). Regardless of the fuel used, Small cars are most numerous and their Big counterparts the least. The typical engine power of these cars is about 60–80 kW. The engine volume is correlated to the car weight, which is related to the fuel efficiency as follows: $FE = 0.004 + 5.249\ W$ ($R^2 = 0.839$) (*FE* is fuel efficiency, i.e., the average fuel consumption (l/100 km)); *W* is the car weight (kg)). In addition, the fuel consumption of an average car using petrol, diesel, and/or gas amounts to 6.7 l/100 km (0.683 kW-h/km). Specifically, the average fuel consumption of an average petrol car is 7.3 l/100 km (0.706 kW-h/km) (this is expected to decrease to 5.8 l/100 km (0.561 kW-h/km) by 2020), and that of an average diesel/gas car 5.8 l/100 km (0.594 kW-h/km), which is expected to decrease to 4.6 l/100 km (0.493 kW-h/km) by 2020. The average age of a passenger car in the EU-27 is 7.5 years (this is expected to increase to about 11–13 years by 2020) (IPTS 2003; ICG 2010).

Emissions of GHG by conventional ICEVs are usually considered as closely related to their WTW energy/fuel efficiency. In many cases, both can be standardized and as such become country or region specific. For example, the standards set up for the EU-27 Member States in 2007–2008 were 6–8 l/100 km (0.612–0.760 kW-h/km) of energy/fuel consumption and 165–200 gCO_2/km. The newly proposed standards are around 6.2 l/100 km (0.632 kW-h/km) and 140 g CO_2/km. The targets to be achieved by 2030 are energy/fuel consumption of about 3.5 l/100 km (0.357 kW-h/km) and emissions of about 82–84 gCO_2/km (CO_2—Carbon Dioxide) (IPTS 2008).

HYVs (Hybrid Vehicle(s))

HYVs (Hybrid Vehicle(s)) can be considered an advanced passenger car technology. They are powered by conventional petrol or diesel ICEs and an electromotor. While the former uses petrol or diesel fuel, the latter uses electric energy stored in on-board batteries, which are charged by the energy from the ICE engine. This means that recharging batteries by plugging in at street stations and/or at home is not possible. In general, the electromotor is used for driving at low speeds predominantly in urban areas, while the power switches to ICE when driving at higher speeds requiring greater engine power. The WTW energy/fuel efficiency of these cars is about 40 % (Toyota Prius) and is expected to improve to about 55 % in the mid-term future. For example, the most efficient hybrid car in 2005 was the Honda Insight whose WTW energy/fuel efficiency was 0.64 km/MJ (0.391 kW-h/km) followed by the Toyota Prius with 0.56 km/MJ (0.491 kW-h/km), and the petrol

ICE Honda Civic VX with 0.52 km/MJ (0.534 kW-h/km) (MJ—Mega Joule; kW-h—kilowatt hour).

In general, in 2010, the fuel consumption of an average hybrid electric-petrol car amounted to about 5.4 l/100 km (0.799 kW-h/km) and that of an average hybrid electric–diesel car to about 4.51 l/100 km (0.483 kW-h/km). The corresponding emissions of GHG were 125 and 90 gCO_2/km, respectively. Some improvements particularly to the fuel supply systems in these cars lead to expectations that their consumption will decrease to about 3.4 l/100 km (0.329 kW-h/km) in the former and to about 2.45 l/100 km (0.251 kW-h/km) in the latter by 2035. The corresponding emissions of GHG will be 52 and 47 gCO_2/km, respectively. This implies that in terms of energy/fuel efficiency and related emissions of GHG, electric/petrol and electric/diesel HYVs are more efficient than their conventional ICE counterparts by about 25 and 30 %, respectively (Bodek and Heywood 2008).

BEVs (Battery Electric Vehicles)

BEVs (Battery Electric Vehicle(s)) can be considered as an advanced passenger car technology. They are propelled by electromotors using the electric energy stored in batteries on-board the vehicle. The batteries are recharged from the power grid (at home or at street/shop charging stations). The WTW energy efficiency of electric cars is expected to reach up to about 80 %. This can be achieved, among other factors, also thanks to converting the stored energy into propelling the car, not consuming energy while stopping, and regenerating some (about 20 %) through regenerative braking. For example, the Tesla Roadster BEV has a WTW energy efficiency of about 1.14 km/MJ (0.235 kW-h/km). Other typical electric cars are expected to have a WTW energy efficiency of about 1.125 km/MJ (0.247 kW-h/km) (Hamilton 1980) and 1.583 km/MJ (0.175 kW-h/km) (Toyota Rav4EV) (ICG 2010). It should be mentioned that about 20 % of this energy consumption is due to inefficiencies in recharging the on-board batteries. These are the most sensitive parts of electric cars in terms of their specific energy capacity versus the weight, replacement, durability, and the short and full charging time. With a single charge, they need to provide sufficient energy for the car to cover a reasonable distance at a reasonable speed as compared to conventional ICE petrol/diesel cars. Contemporary lithium batteries usually have a specific energy capacity of about 130 W-h/kg, which is one of the reasons for their frequent use despite their rather limited lifespan. Modified lithium iron phosphate and lithium–titan batteries have an extended life span of up to several thousand cycles and are relatively easily replaced. Their recharging time also needs to be reasonable. This is not particularly important if recharging takes place at home during off-peak hours (Koyanagi and Uriu 1997); however, it becomes very important if recharging takes place at street stations. Depending on the car's charger and battery technology, the recharging time can be 10–30 min to fill the batteries to about 70 % of their capacity. For example, the forthcoming models in the EU-27 market in 2011 such as Nissan Leaf, Renault Fluence Z. E. and Hyundai Blue have

ranges between 140 and 170 km, top speeds between 130 and 145 km/h, full charging times of 6–8 h, and rapid charging times (up to 80 %) of about 25–30 min. The above-mentioned characteristics make these cars particularly convenient for use in urban and suburban areas with rather short daily driving distances (ICG 2010).

Electricity for BEVs can be obtained from different primary nonrenewable and renewable primary sources (EEA 2008; OI 2011). The former include coal, crude oil, natural gas, biomass, and nuclear energy, and the latter solar, wind, and hydro energy. The shares of the above-mentioned primary sources (usually country or region specific) make GHG emissions by BEVs exclusively dependent on their WTT (Well-To-Tank) energy/fuel efficiency.

HVs (Hydrogen Vehicles) and HFCVs (Hydrogen Fuel Cell Vehicle(s))

Hydrogen passenger vehicles (cars) are powered by hydrogen fuel. Two categories of these vehicles can be distinguished. The first are slightly modified conventional ICEs that use hydrogen instead of petrol/diesel/gas as fuel—HVs (Hydrogen Vehicle(s)). In order to cover a reasonable distance, hydrogen is highly compressed in the fuel storage tanks of these vehicles, mainly thanks to its low density. HFCVs (Hydrogen Fuel Cell Vehicle(s)) represent an advanced technology in passenger cars. They consist of five components which distinguish them from their HV counterparts: their fuel cell stack, electric motor, power control unit, hydrogen storage tank, and high-output batteries. Specifically, the fuel cell stack consists of individual fuel cells whose number depends on their size and the required electric energy. Each fuel cell uses either pure hydrogen from hydrogen-rich sources, or oxygen to generate electric energy. Fuel is used to feed the electric motor that actually propels the car. The intensity of electric energy delivered from the fuel cells to the electric motor is regulated by the power control unit. Hydrogen as the source of electricity is stored in the hydrogen storage tank either as a liquid or as a highly compressed gas. In addition, high-output batteries are installed to accumulate the electric energy from the regenerative braking, thus providing additional power to the electric motor.

Hydrogen as a prospective fuel exists in nature as a component of natural gas (CH_4) and water (H_2O). This means that in order to provide hydrogen as fuel for hydrogen fuel cell cars, it needs to be extracted from the above-mentioned sources. This can be carried out by reforming natural gas or through the water electrolysis either at large plants or at local fuel supply stations. In the former case, distribution from the producing plants to local supply stations needs to be provided either by truck or an underground pipeline network. Hydrogen has more energy per unit of mass than other crude oil-based fuels including natural gas. On the other hand, it is much less dense (Janic 2010). The design of the fuel tanks of HFCVs will have to take the above-mentioned facts into consideration. Nevertheless, the volume of these tanks should not be much greater than that of conventional ICEVs as more energy per unit of mass of hydrogen is expected to compensate its lower density to

a large extent. In addition, this will enable a similar pattern of utilization of HFCVs compared to their modern conventional ICEV counterparts.

The primary sources for obtaining hydrogen heavily influence the energy/fuel efficiency of HFCVs. At present, in practice, the WTW energy efficiency of HFCVs reaches about 50–60 % (i.e., 0.85 km/MJ or 0.327 kW-h/km) if hydrogen is obtained from reforming natural gas, and to only about 22 % (i.e., 0.30 km/MJ or 0.926 kW-h/km) if it is obtained through water electrolysis. However, the theoretical overall efficiency of HFCVs can be nearly 100 % (i.e., 1.39 km/MJ or 0.198 kW-h/km and 2.78 km/MJ or 0.102 kW-h/km, respectively) (http://www.fueleconomy.gov/FEG/fuelcell.shtml).

If hydrogen is derived from water electrolysis, the emissions of GHG by HFCVs will mainly depend on the primary sources of the electric energy used for this electrolysis. This can be from both nonrenewable and renewable sources, which influences the total WTW emissions of GHG. In the WTT segment, these will be zero if electricity is obtained exclusively from renewable sources and much higher otherwise. In the TTW segment, the emissions will be zero except for those of water vapor (H_2O), which will increase by about three times as compared to those from conventional ICEV and HYV fuels (Janic 2010).

4.2.2.3 Modeling Performances

Modeling the performances of different passenger car technologies is focused on their environmental performances in terms of the energy/fuel consumption and related emissions of GHG. When and where necessary, other infrastructural, technical/technological, operational, economic, and social policy performances are also considered. Modeling includes an analysis of the previous efforts, objectives, and assumptions, as well as the basic structure of the methodology for assessing the above-mentioned impacts/effects on the environment.

Previous efforts

Alterative passenger car technologies and particular dimensions of their performances (technical/technological, operational, economic, environmental, social, and policy) have been intensely investigated over the past decade. In general, efforts can be classified into the following five segments:

- *Market demand*: This aspect has focused on investigating the demand for alternative energy/fuel passenger cars and the consequent prospective market structure, while respecting the various operational, economic, environmental, and institutional (policy) conditions/constraints. These particularly relate to demand for HYVs and BEVs in specified regions. In such context, different supporting tools mainly based on the logit modeling approach have been developed for estimating the relative market share and the dynamics of introducing particular passenger car technologies, as well as their absolute demand

and supply with both and particularly the latter respecting the long-term plans of major car manufacturers (Ewing et al. 1998; Hörmandinger and Lucas 1996; Heffner et al. 2007; Higgins et al. 2007; ICG 2010; IPTS 2003; Kurani et al. 1996; Mabit and Fosgerau 2011).

- *Impacts and effects of energy consumption and emissions of GHG in urban areas*: This aspect has focused on investigating the characteristics of energy/fuel consumption by conventional ICEVs, HYVs, and new BEVs and HFCVs, the overall logistics for the energy/fuel supply, estimating the demand for the particular energy/fuel type, and the impacts of this demand on the eventual depletion of these energy/fuel primary sources. In the above-mentioned cases, the related emissions of GHG affecting the environment at the specified urban, suburban, and wider regional scale have also been estimated (Chi and Stone 2005; Coelho and Luzia 2010; DeLuchi 1989; Georgakellos 2008; Hamilton 1980; IPTS 2008; Johansson and Åhman 2002; Kang and Recker 2009; Kempton and Letendre 1997; Koyanagi and Uriu 1997; Lave and MacLean 2002; Nakata 2000; Rienstra and Nijkamp 1998; Schock et al. 1995; Wang and DeLucchi 1991; Wang et al. 2008).
- *Design and performance of new passenger car technologies including infrastructure for energy/fuel supply*: This aspect has dealt with the technical/technological solutions (material, design, safety requirements) influencing the operational, economic, and safety performances of innovative (HYV) and new (BEV and HFCV) technologies. In addition, the characteristics and needs for energy/fuel supply infrastructure for new passenger car technologies have been investigated (Chen and Ren 2010; Eberhard and Tarpening 2006; Ogden 1997; Schwoon 2007; Spiegel 2004).
- *Social costs and benefits*: This has focused on assessing the overall social and environmental costs and benefits from using innovative HYVs and new BEVs and HFCVs including the economy of providing and using energy/fuel by these cars in specified regions (Funk and Rabl 1999; Haller et al. 2008; Johansson 1999); and
- *Policy implications due to introducing alternative passenger car technologies*: This research has analyzed energy/fuel economy in various regions of the world and related emissions of green house gases, and compared them with the standards set up for passenger cars and other transport vehicles (An and Sauer 2004).

Assumptions

The methodology for assessing the prospective medium- to long-term effects of the above-mentioned advanced passenger car technologies on energy consumption and related emissions of GHG (CO_{2e}—Carbon Dioxide equivalents) has been developed respecting the following facts:

- The fuel/energy consumption and related emissions of GHG depend on the volumes of passenger car use, which is mainly driven by the overall socio-economic development;

- The energy/fuel used by currently predominant conventional ICEVs is obtained from exhaustive resources (crude oil), the burning of which generates emissions of GHG, which after being deposited tend to remain in the atmosphere for a long time;
- The structure of the passenger car market is expected to gradually change due to the more intensive use of advanced HYVs, BEVs, and HFCVs, in addition to permanent improvements of conventional ICEVs; and
- Production of electric energy used by BEVs and indirectly by HFCVs is expected to generally shift toward more intensive use of renewable sources.

In addition, the methodology is based on the following assumptions:

- The particular passenger car technologies remain and/or penetrate the market of a given region according to the specified "what-if" scenarios, which remain stable (constant) over a given period of time; this approach has been adopted since it is at present practically impossible to precisely predict the structure of this market based on the users' acceptance of BEVs and HFCVs even in the short- and especially in the medium- and long-term future;
- The average (typical) values of the WTW energy/fuel efficiency for particular passenger car technologies and related emissions of GHG and their gradual improvements are implicitly taken into account; energy consumption is estimated only in relative terms (per unit of car output—veh-km) and used as an input for calculating the GHG emissions;
- The emissions of GHG by passenger car use over the specified future period of time are exclusively considered; this implies that the lifetime and related rates of dissipation of GHG have not been taken into account mainly due to the very high level of uncertainty and diverging expert opinions on these issues; and
- Advanced passenger car technologies are assumed to use energy/fuel mainly obtained from GHG-neutral primary sources whose shares are also specified according to the "what-if" scenarios remaining stable (constant) over the given period.

Structure of the methodology

The methodology consists of three components/models: (i) the model for estimating the volumes of passenger car use; (ii) the model for estimating the fuel/energy consumption by the above-mentioned passenger car use; and (iii) the model for estimating emissions of GHG from the above-mentioned fuels/energy consumption.

The model for estimating the passenger car use

The existing and future passenger car use in terms of the vehicle kilometers carried out during a given period of time (year) in a given region can be estimated by two types of submodels using empirical data: (i) the time series model; and (ii) the causal model based on multiple regression analysis.

- **The time series submodel**

The time series model uses the empirical data on the passenger car use for the period and establishes their relationship in dependence of time as follows:

$$v_k = f(t^n) \tag{4.1a}$$

where

v_k is the volume of passenger car use in the k-th year of the observed period ($k = 1,2,\ldots, N$);

t^n is the variable representing time (years of the observed period); and

n is the coefficient estimated by establishing the given relationship.

The submodel (Eq. 4.1a) can be estimated using past data, thus enabling extrapolation of the passenger car use as the dependent variable into future period of time (the independent variable). In this case, it is implicitly assumed that the main forces influencing the dependent variable in the past period will continue to similarly drive future development.

- **Causal submodel**

This submodel implies that the passenger car use in a given region over a given period (the dependent variable) depend on a set of influencing factors considered as the independent (explanatory) variables. One of the possible generic forms in the given context is as follows:

$$v_k = f(t^n) \tag{4.1b}$$

where

GDP_k is the Gross Domestic Product of a given region in the k-th year of the observed period (billion currency units);

MR_k is the motorization rate of a given region in the k-th year of the observed period (cars/thousand inhabitants); and

P_k is the population of a given region in the k-th year of the observed period (million).

The other symbols are analogous to those in Eq. 4.1a.

In Eq. 4.1b, the past data of one or more independent variables can be simultaneously taken into account to estimate the dependent variable. By specifying the future values of particular independent variables, the future volumes of passenger car use in the given region can be estimated (as the dependent variable). Similarly as in Eq. 4.1a, the driving forces from the past are expected to act in a very similar way in the future.

The model for estimating energy consumption by passenger car use

Let the period of time considered be N years long. During this period, M different passenger car technologies are expected to be used. The average fuel/energy consumption of the passenger car technology (i) in the k-th year of the observed period can be estimated as follows:

$$E_{ki} = v_k * p_{ki} * (1 - r_{ki}) * e_{ki} \tag{4.2a}$$

where

p_{ki} is the proportion (i.e., market share) of passenger car technology (i) in the k-th year of the observed period;

r_{ki} is the average rate of improvement of the fuel/energy efficiency of passenger car technology (i) in the k-th year of the observed period; and

e_{ki} is the average energy/fuel consumption of passenger car technology (i) in the k-th year of the observed period (units of energy/fuel/car-km).

From Eq. 4.2a, the total cumulative energy/fuel consumption from the beginning to the year (n) of the observed period can be estimated as follows:

$$E(n) = \sum_{k=1}^{n} \sum_{i}^{M} E_{ki} = \sum_{k=1}^{n} \sum_{i}^{M} v_k * p_{ki} * (1 - r_{ki}) * e_{ki} \tag{4.2b}$$

where all symbols are analogous to those in the previous equations.

The model for estimating emissions of GHG by passenger car use

Based on Eqs. 4.2a and 4.2b, the emissions of GHG by the passenger car technology (i) in the k-th year of the observed period can be calculated as follows:

$$GH_{ki} = E_{ki} * g_{ki} \tag{4.3a}$$

where

g_{ki} is the average emission rate of GHG of the passenger car technology (i) in the k-th year of the observed period (emitted quantity/unit of energy/fuel consumed)

In Eq. 4.3a, the variable g_{ki} takes into account both direct and indirect (WTW) emissions of GHG emitted by the given passenger car technology in the given year. In addition, it depends on the structure of primary sources for obtaining energy/fuel for a given car technology in the given year as follows:

$$g_{ki} = \sum_{j=1}^{L} q_{kij} * \gamma_{kij} \tag{4.3b}$$

where

q_{kij} is the share of the primary source of type (j) for producing fuel/energy for the car technology (i) in the k-th year of the observed period;

γ_{kij} is the average rate of GHG emissions from producing the energy/fuel from the primary source (j) for the car technology (i) in the k-th year of the observed period (emitted quantity/unit of energy/fuel consumed); and

L is the number of different primary sources for producing the energy/fuel for passenger car technologies.

The cumulative GHG emissions from energy/fuel consumption due to the passenger car use from the beginning until the year (n) of the observed period are estimated as follows:

$$G(n) = \sum_{k=1}^{n} \sum_{i}^{M} G_{ki} = \sum_{k=1}^{n} \sum_{i}^{M} E_{ki} * g_{ki} \tag{4.3c}$$

where all symbols are as in the previous equations.

Application of the methodology

Input

- **"What-if" scenario approach**

The "what-if" scenario approach is characterized by specifying the particular variables of the proposed above-mentioned methodology for the specified medium- to long-term period, in this case from 2010/15 to 2065 (Rienstra and Nijkamp 1998). This includes GDP growth as the main driving force of the volumes of passenger car use, the composition of the passenger car fleet in terms of the share of particular car technologies, the characteristics of particular car technologies in terms of the energy/fuel consumption and related emissions of GHG respecting gradual improvements over time, and the composition of primary sources for obtaining the energy/fuel to be used by the particular car technologies. Three scenarios are considered:

- *Scenario 0* is a rather hypothetical one specified mainly for comparative purposes. It is characterized by the continuing exclusive use of conventional petrol/diesel/gas ICEVs whose WTW energy efficiency and related rates of emissions of GHG continuously improve by 2030/2035. Their hybrid counterparts are not expected to penetrate the market substantially. In addition, depletion and vanishing crude oil reserves and increased related emissions of GHG do not particularly affect the expected use of these permanently technical/technologically improved conventional passenger cars.
- *Scenario 1* is a semi-hypothetical scenario containing some remaining uncertainty regarding the extent to which advanced, conventional petrol/diesel/gas ICEVs, and their HYV versions with constantly improving WTW energy/fuel efficiency and related emissions of GHG are assumed to be exclusively used. This again implies that further depletion of crude oil reserves will not significantly affect the use of these passenger car technologies. In addition, the emissions of GHG will be controlled by the technical/technological improvements of advanced innovative HYVs and existing ICEVs. Also, advanced BEVs and HFCVs are not assumed to substantially penetrate the market.
- *Scenario 2* can be considered realistic as it implies depletion of crude oil reserves and the subsequent strong market penetration of advanced passenger

car technologies (BEVs and HFCVs). In addition, there will be a constant increase in the use of renewable primary sources to produce the energy/fuel for these cars. According to some forecasts, the known reserves of crude oil will be mostly exhausted by the end of the specified period (around 2065) (Cambell 2002; Greene and Hobson 2003; Pfeiffer 2004; IEA 2009). The petrol and diesel fuels obtained from biomass and synthetic fuels will not be sufficient and will consequently be too expensive and thus practically unavailable for mass passenger car use. This implies that conventional petrol/diesel/gas ICEVs and their hybrids (HYVs) will gradually but certainly disappear from the market, which will be exclusively shared between BEVs and HFCVs.

During the observed period, which is divided into three subperiods, a set of factors are assumed to individually or in combination influence the rate of market penetration of each advanced passenger car technology as follows:

– The technical/technological maturity of the advanced car technology and availability of the energy supply infrastructure in the given region (EU27);
– The familiarity of prospective users with advanced car technologies as compared to existing conventional technologies;
– Comparable/competitive purchasing prices and operating costs of advanced car technologies as compared to existing conventional technologies;
– Despite improvements in the TTW (Tank-To-Wheel) efficiency, continuously raising operating costs of conventional petrol/diesel/gas ICEVs and their hybrids mainly due to raising prices of the increasingly depleting/vanishing crude oil reserves;
– Gradual saturation of the market with advanced car technologies implying the market presence of competitive advanced technologies; and
– The overall increasing public awareness of the depletion of crude oil reserves as the fuel source for conventional ICEVs and their hybrids on the one hand, and of BEVs and HFCVs as the only available alternatives on the other.

In the first subperiod, the annual market penetration rate of new passenger cars is assumed to be rather modest due to the predominant influence of factors 1 and 2. In the second period, this rate is assumed to be reasonably high, stable, and influenced mainly by the above-mentioned factors 3 and 4. In the final period, this rate is assumed to again decrease mainly due to the influence of factors 5 and 6.

During the same period, energy for the transport sector and passenger cars is assumed to be increasingly produced from renewable primary sources on account of coal, crude oil, and natural gas exhaustion (OI, 2011).

- **The volumes of passenger car use**

The volumes of passenger car use in the given region are estimated by using the past GDP data as the independent variable in the expression (4.1b) as shown in Fig. 4.1. Implicitly, the average car occupancy rate is adopted to be 1.6 persons/vehicle.

The growth of volumes of passenger car use in the EU27 between 1995 and 2009 closely followed GDP growth, albeit at a decreasing rate. Consequently, the

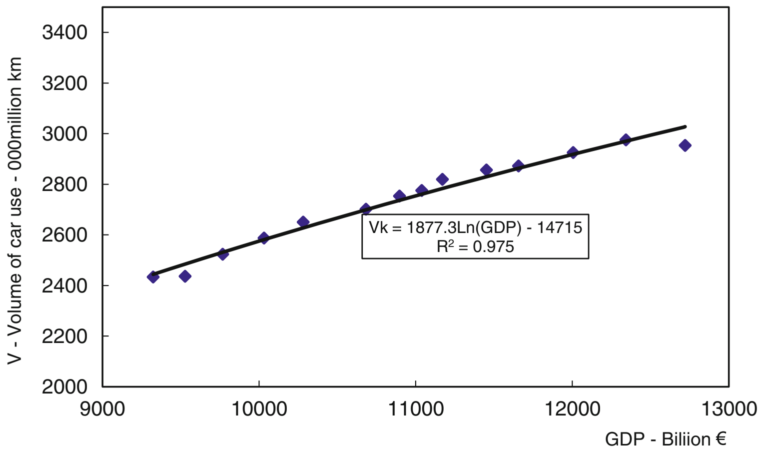
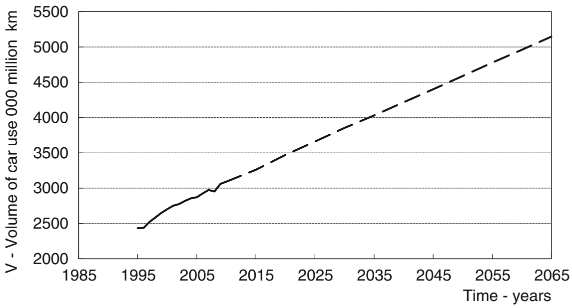


Fig. 4.1 Relationship between the annual volumes of passenger car use and GDP in the EU27 (1995–2009) (EC 2010)

Fig. 4.2 Development of the volumes of passenger car use over time in the EU27 (2010–2065)



volumes of passenger car use over the forthcoming 2010/15–2065 period are estimated using the constant average annual growth rate of GDP of 2 % (as in the past period) as shown in Fig. 4.2.

The volumes of passenger car use in the EU27 are expected to continue to increase during the observed future period at a slightly decreasing rate mainly driven by the rather constant and stable GDP growth.

- **Market share of different passenger car technologies**

Considering the above-mentioned factors, the annual rates of market penetration by the particular advanced passenger car technologies in each of the three sub-periods of the observed period are determined for Scenario 0, 1, and 2, as shown in Fig. 4.3a, b, c (ICG 2010).

In all the above-mentioned scenarios, the proportion of conventional petrol ICEVs is expected to decrease to a modest 10 % in Scenario 0 and 0 % in Scenarios 1 and 2. The proportion of conventional diesel ICVs is expected to increase

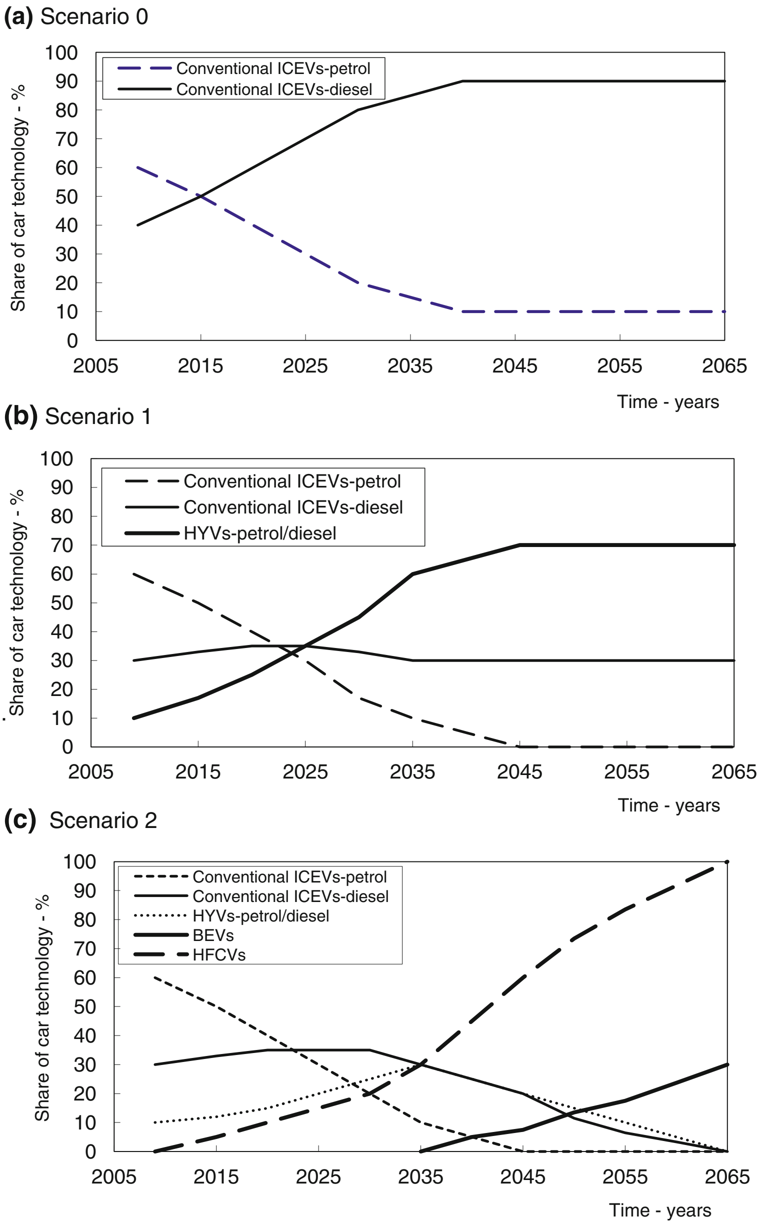


Fig. 4.3 Scenarios of the market penetration by different passenger car technologies in the given example (EU27–2010/15-2065)

up to 90 % in Scenario 0, increase and then decrease and stabilize at about 30 % in Scenario 1, and increase and then continuously decrease to 0 % until the end of the observed period in Scenario 2. The proportion of HYVs is expected to increase in

Scenario 1 during the first two-thirds of the observed period to 70 %, and to 35 % during the first half of the observed period in Scenario 2. This proportion remains at the achieved level in Scenario 1 and decreases to 0 % in Scenario 2 during the remaining observed period. From the time of entering the market, the proportion of BEVs and HFCVs is expected to increase in Scenario 2 and reach about 70 and 30 %, respectively, by the end of the observed period.

- **Energy/fuel consumption and emissions of GHG**

The average rates of energy/fuel consumption and emissions of GHG of different passenger car technologies expected to be used in the EU27 during the observed period are given in Table 4.1.

In order for conventional ICEVs and their hybrid versions to fulfill the above-mentioned targets, improvements in both WTT (Well-To-Tank) and particularly TTW (Tank-To-Wheel) efficiency will be needed. In the former case, such improvements will be rather difficult to achieve, while in the latter, improvements will mainly stem from advanced car design including increased use of generally lighter (composite) materials. In any case, the average annual rate of improvements of the WTW efficiency and related emissions of GHG by 2020/2035 will need to be about 4–5 % for conventional petrol ICEVs, 4.5–5.5 % for conventional diesel ICEVs and 4.7–5.7 % for HYVs. The WTW (Well-To-Wheel) energy efficiency of BEVs and HFCVs will also improve while their emissions of GHG will strongly depend on the primary sources for the production of electric energy (EU-27- 2010/15-2065).

Table 4.1 Environmental performances of the different passenger car technologies—energy/fuel consumption and emissions of GHG (Bodek and Heywood 2008; IPTS 2003; ICG 2010; IEA 2009; http://www.fueleconomy.gov/FEG/fuelcell.shtml)

Technology	Basic energy/ fuel	Efficiency 0	WTW energy efficiency (kWh/km)	WTW emissions of GHG (gCO_{2e}/km)
Conventional ICEVs	Petrol/diesel/	20–21	0.612–0760	165–200
	Auto gas (e)	25	0.955	
	Petrol/diesel/	20–21	0.632	140
	Auto gas (n)	–	–	–
	Petrol/diesel/	20–25	0.357	82–84
	Auto gas (f)	–	–	
HYVs	Petrol (e)	40	0.799	125
	Diesel (e)	55	0.483	90
	Petrol (e)	50	0.329	52
	Diesel (e)	65	0.251	47
BEVs	Electricity	80	0.175–0.235	(A)
HVs	Hydrogen	50	0.926	(A)
HFCVs	Hydrogen	95–100	0.010–0.327	(A)

e existing standards*;* *n* new proposed standards to be in place by the year 2020–2035; *(A)* depending on the primary sources for producing electricity and/or hydrogen

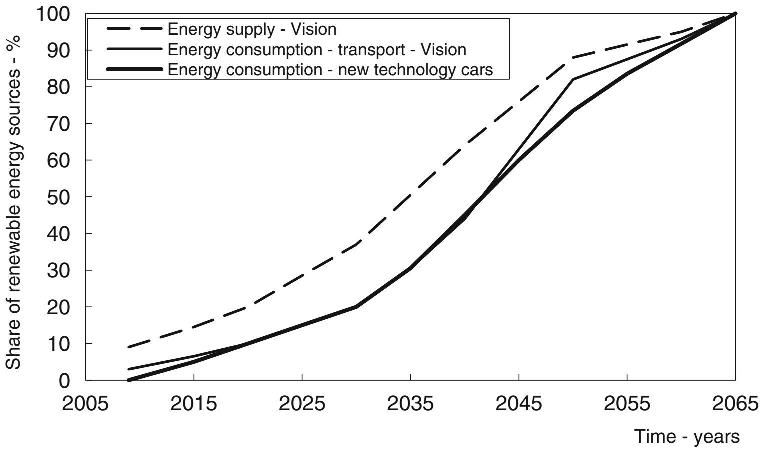


Fig. 4.4 Development of the share of renewable primary sources in the energy supply and consumption by the transport sector and advanced passenger car technologies (EU27–2010/15-2065) (EEA 2008; OI 2011)

- **Primary sources for energy/fuel supply and consumption**

A scenario of developing the share of renewable primary sources in the energy/fuel supply and the energy consumption by the transport sector and particularly by advanced passenger car technologies is shown in Fig. 4.4.

The share of renewable primary sources in the energy supply is expected to continuously grow during the given period according to the "S-curve power law." This implies relatively modest growth rates at the beginning, higher in the middle, and again lower at the end of the observed period. Such dynamism is reasonable if the EU-27 Member States intend to mitigate their currently increasing dependency on imported and increasingly expensive depleting crude oil sources. Since these reserves are expected to be exhausted by the end of the observed period, renewable sources will remain the exclusive primary energy supply sources in the region. A substantial proportion of such energy will be consumed by the transport sector—in proportion to that of the overall supply. This electricity will be mainly consumed by the advanced passenger car technologies dominating the transport sector during the observed period according to Scenario 2.

Results

The results in terms of the annual energy consumption and related emissions of GHG in particular Scenarios of passenger car use in the EU27 states during the observed period are shown in Figs. 4.5, 4.6, and 4.7.

- **Energy consumption**

The annual energy consumption by passenger car use in the given example is shown in Fig. 4.5. The energy consumed is expressed in terms of crude oil equivalents for comparative purposes.

As intuitively expected, the annual energy consumption differs in different scenarios. In addition, it changes over the observed period driven mainly by the volumes of passenger car use on the one hand, and particular passenger car technologies in combination with improvements of their WTW energy efficiency on the other. In particular, in Scenario 0, the annual energy consumption decreases at the beginning of the observed period despite growing volumes of passenger car use mainly thanks to improvements in the energy efficiency of conventional (petrol/diesel/auto gas) ICEV passenger cars (Table 4.1). When these improvements are exhausted, the annual energy consumption begins and continues to increase until the end of the observed period mainly driven by growing volumes of passenger car use. In Scenario 1, the trend of changing the annual energy consumption during the observed period is generally similar to that in Scenario 0. The differences are as follows: the annual energy consumption is always lower than that in Scenario 0 mainly thanks to more intensive use of energy efficient HYV cars; the period in which the energy consumption decreases despite growth in the volumes of passenger car use is longer due to the longer period of exhaustion of improvements in the WTW energy efficiency of all three car technologies (Table 4.1). In Scenario 2, the annual energy consumption is the lowest as compared to that in the other two scenarios. It continuously decreases despite the growing volumes of passenger car use during the observed period (2010/15-–2065). This is achieved by the more intensive and continuous introduction of EVs on the one hand, and much more energy efficient BEVs, HVs, and HFCVs on the other (Fig. 4.3 and Table 4.1).

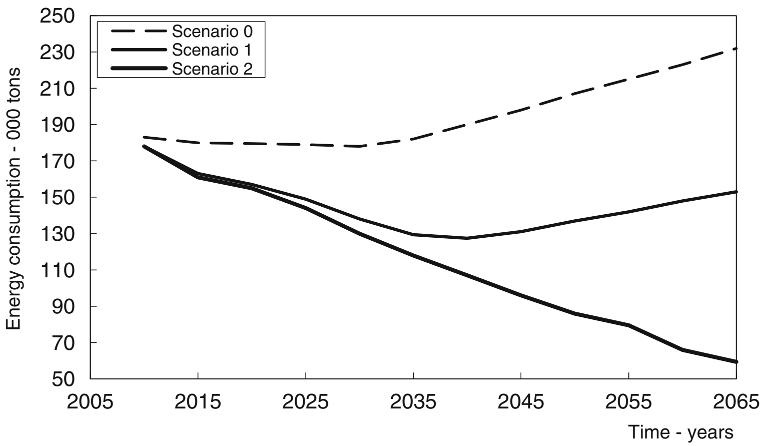


Fig. 4.5 Energy consumption over time in particular scenarios (EU27—period 2010/15–2065)

- **Emissions of GHG**

Emissions of GHG in terms of CO_{2e} are estimated using the above-mentioned inputs. The results are shown in Figs. 4.6 and 4.7.

In particular, Fig. 4.6 shows the annual emissions of CO_{2e} by passenger car use in the given example (EU27—period 2010/15–2065).

The general trends in particular Scenarios are similar to those of energy consumption. In particular, in Scenarios 0 and 1, the annual emissions of GHG (CO_{2e}) decrease during the first part and then increase until the end of the observed period. The main cause of this is the fact that during the first part of the period, the annual rate of technical/technological improvements to passenger cars (only ICEVs in Scenario 0 and both ICEVs and HYVs in Scenario 1) is higher than the annual rate of increasing volumes of their use. After the above-mentioned improvements are exhausted, these emissions again start to increase by the end of the observed period mainly driven by increasing annual volumes of passenger car use. During the entire observed period, the annual emissions of GHG (CO_{2e}) are greater in Scenario 0 than in Scenario 1, thus indicating the contribution of the HYVs to their mitigation (by about 10–15 %). In Scenario 2, the gradually increased use of advanced BEVs and HFCVs contributes to decreasing annual emissions of GHG (CO_{2e}) over the entire observed period. In addition, in each individual year of this period, these emissions are lower than those in Scenarios 0 and 1. At the same time, at the end of the observed period (in 2065), the annual emissions may be close to zero due to providing the energy/electricity for both advanced passenger car technologies prevailing in the market exclusively from renewable primary sources.

The cumulative emissions of GHG (CO_{2e}) by the given year of the observed period (EU27–2010/15–2065) are shown in Fig. 4.7.

In Scenarios 0 and 1, the cumulative emissions of GHG (CO_{2e}) increase continuously during the observed period. Specifically, they increase during the first

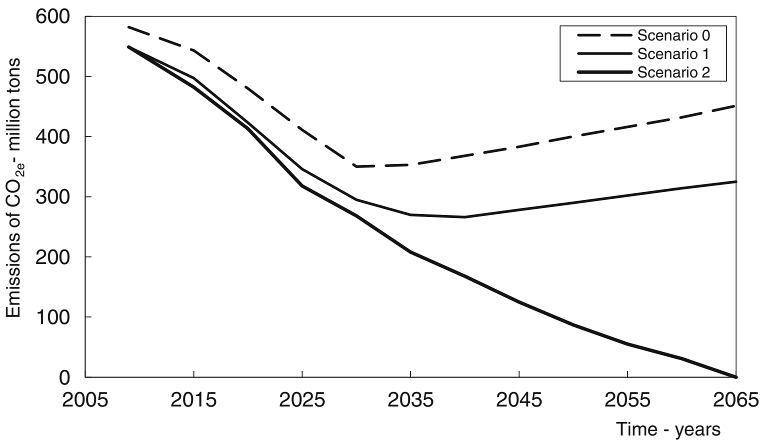


Fig. 4.6 Emissions of GHG (CO_{2e}) over time in particular scenarios (EU27–2010/15–2065)

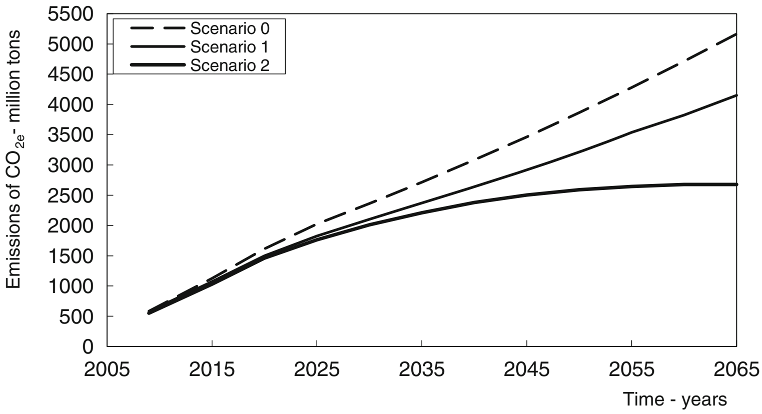


Fig. 4.7 Cumulative emissions of GHG (CO_{2e}) by given year of the observed period in particular scenarios (EU27–2010/15–2065)

part of the period at a decreasing rate mainly thanks to improvements of conventional ICEVs and both ICEVs and HYVs, respectively, despite continuous growth in passenger car use volumes. Over the remaining part of the period, when the improvements are exhausted, GHG emissions continue to grow mainly driven by and in proportion to the growing volumes of passenger car use. Again, the cumulative emissions of GHG (CO_{2e}) in Scenario 0 will always be greater than those in Scenario 1, with increasing differences over the observed period. This illustrates the increasing positive contribution of the more intensive use of HYVs over time. In Scenario 2, BEVs and HFCVs will contribute to increasing the cumulative emissions of GHG (CO_{2e}) at a decreasing rate during the entire observed period. They are mainly driven by the growth of volumes of passenger car use. Near the end of the observed period, when both advanced passenger car technologies prevail in the market, the cumulative emissions stagnate. In other words, in light of the long standing time of CO_2 in the atmosphere, these are actually emissions from ICEVs and HYVs before their replacement by their BEV and HFCV counterparts. Last but not least, the cumulative emissions of GHG (CO_{2e}) in Scenario 2 will always be lower than those in Scenarios 0 and 1. The positive differences continuously increase and reach the maximum at the end of the observed period.

4.2.3 Evaluation

Advanced passenger car technologies and their variations including electric petrol/diesel HYVs (Hybrid Vehicles), BEVs (Battery Electric Vehicles), and HFCVs (Hydrogen Fuel Cell Vehicles) possess both advantages (Strengths and Opportunities) and disadvantages (Weaknesses and Threats).

Advantages

- Decreasing total energy consumption in terms of crude oil equivalents and related emissions of GHG in terms of CO_{2e} (Carbon Dioxide equivalents) despite increasing volumes of passenger car use thanks to the technical/technological improvements of conventional ICEVs and HYVs at higher rates of growth of passenger car use volumes during the first part of the observed period; and
- Decreasing total energy consumption and related emissions of GHG during the entire observed period despite growing volumes of passenger car use after BEVs and HFCVs penetrate the market more substantially.

Disadvantages

- Contributing to increasing total energy consumption and related emissions of GHG until the end of the observed period mainly driven by continuously growing volumes of passenger car use after the potential for further improvements of ICEVs and HYVs is exhausted; the energy consumption and related emissions of GHG will be lower insofar as HYVs penetrate the market at a higher rate;
- Considering the lifespan of man (car)-made emissions of GHG in the atmosphere of several hundred years, only complete replacement of conventional ICEVs and HYVs with their BEV and HFCV counterparts under the given circumstances can actually stop their further cumulative increase in the given case;
- Achieving an energy density of batteries close to that of gasoline and diesel fuel as derivatives of crude oil, enabling the equivalent driving performances (acceleration, operating speed, and range with a single battery charge) as those of ICEVs and HYVs is going to be complex;
- Achieving a selling price comparable to that of both BEVs and HFCVs is uncertain; and
- Penetrating the market more intensively will not contribute to reducing congestion in urban and suburban areas.

Finally, advanced passenger cars can be considered a subsystem of the advanced transport system mainly regarding the techniques/technologies of the power system (engine) and the energy/fuel supply system, both of which are adapted to type of energy/fuel used.

4.3 Large Advanced Container Ships

1957	The first Sea–Land Gateway City container ship, a modified tanker loaded with 56 containers, makes its inaugural voyage between the ports of Newark Miami, Houston, and Tampa (U.S.)
1960	The first Grace Line Santa Eliana fully containerized ship begins international container shipping to Venezuela (U.S.)
2006	The then largest Emma Maersk container ship begins commercial operations (Denmark)

4.3.1 Definition, Development, and Use

Advanced freight ships are mainly characterized by improved operational, economic, and environmental performances, the latter in terms of energy consumption and related emissions of GHG (Green House Gases), as compared to those of their conventional counterparts. The improvements in performances of these ships can generally be achieved by improving existing and/or deploying completely new (advanced) technologies and operations. In particular, due to the continuously increasing use of containers for transporting freight/goods in international trade, improvements of performances will be particularly relevant for the relatively fast and continuously growing fleet of container ships.

Maritime shipping has gained a central role in global trade due to the internalization and globalization of the world's economies. During the past three decades, international seaborne trade has continuously grown, and increasing volumes of freight/goods have been transported in containers as shown in Fig. 4.8.

Despite being relatively modest, the volumes of containerized freight/goods have increased faster than the total volumes of freight/goods by their share in the totals of about 2.75 % in 1980, 10.16 % in 2000, and 15.83 % in 2011.

The above-mentioned total freight/goods volumes have been transported by a fleet composed of five types of ships respecting the categories of freight/goods such as oil tankers, dry bulk, general cargo, container, and other ships. Figure 4.9 shows development of the total world's and particularly the container ship fleet.

As can be seen, both have increased almost exponentially over the past three decades. In particular, the share of container ship capacity in the capacity of total fleet has constantly increased from about 1.61 % in 1980 and 8.02 % in 2000 to about 11.5 % in 2011.

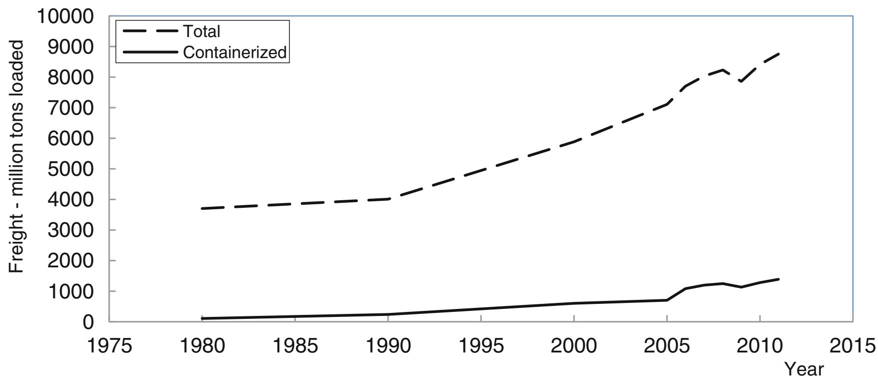


Fig. 4.8 Development of the global international seaborne trade (million tons loaded) (UNCDAT 2012)

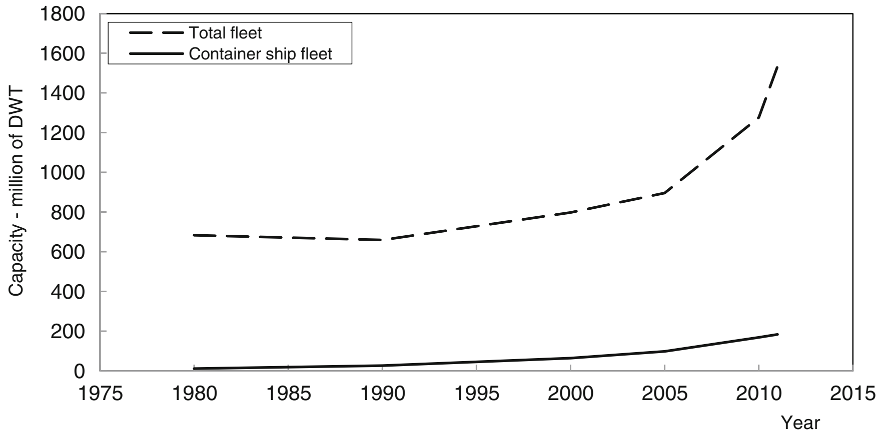


Fig. 4.9 Development of the global freight ship fleet (UNCDAT 2012)

4.3.2 Analyzing and Modeling Performances

4.3.2.1 Background

Container ships have been designed to exclusively carry containers in their holds and on the deck. The fleet of these ships is usually represented by the annual number of ships in operation, their total capacity, the average ship size expressed in TEUs (Twenty foot Equivalent Unit(s)), and DWT (Deadweight Tonnage)[1] as given in Table 4.2.

Evidently, over the past 25 years, the number of container ships has increased fivefold, their total capacity about 15-fold, and the average ship size about threefold. Thus, ships with a capacity exceeding 3,000–4,000 TEU can be considered large container ships, implying that the average ship in 2012 can be considered as a large container ship. It can also be considered advanced if it is more operationally, economically, and environmentally efficient and effective than its conventional predecessors.

Large advanced container ships possess infrastructural, technical/technological, operational, economic, environmental, and social/policy performances. Nevertheless, the aim of dealing with particular performances is primarily to emphasize the contribution of these ships to mitigating impacts on the environment in terms of the energy/fuel consumption and related emissions of GHG (Green House Gases).

[1] This is the total weight (tons) that a given ship can safely carry. It includes payload (cargo), fuel, water, supplies, crew, etc.

Table 4.2 Development of the world's container ship fleet over time (UNCDAT 2012)

Year	Number of ships	Fleet capacity (TEU)	Average capacity (TEU/ship)	Average carrying capacity[a] (DWT/ship)
1987	1,052	12,122,15	1,155	16,170
1997	1,954	3,089,682	1,581	22,134
2007	3,904	9,436,377	2,417	33,838
2008	4,276	10,760,173	2,516	35,224
2009	4,638	12,142,444	2,618	36,652
2010	4,677	12,824,648	2,742	38,388
2011	4,868	14,081,957	2,893	40,502
2012	5,012	15,406,610	3,074	43,036

[a] Based on the standard assumption: 1 TEU = 14 DWT (1 TEU = 2.3 tons of tare weight + 10 tons of average payload; the rest is allocated to the ship's fuel, fresh water, spares and other supplies)

Table 4.3 Development of the container ships over time—milestones in size (MAN Diesel 2011; Rudolf III 2007; www.worldslargestship.com)

Year/generation	Capacity (TEU)	Length (m)	Beam (m)	Draught (m)	Number of engines/power (MW)
1968	750	180	25	9.0	1/6.7
1972	1,500	225	29	11.5	1/14
1980	3,000	275	32	12.5	1/25
1987	4,500	275	39	11.0	1/40.1
1998	7,900	347	43	14.5	1/60
2006/Emma Maersk	15,000	397	56	15.5–16.0	1/80.1
2012/CMA/CGM Marco Polo	16,020	396	54	16.0	2/80
2015/Triple E Maersk	18,000	400	59	16.0	2/64

4.3.2.2 Infrastructural Performances

The main infrastructural performances of large advanced container ships are the required space and other conditions at the port container terminals used to handle them. The required space refers to the number and length of berths, which can be constructed along linear or sheltered coastline. The length of a berth is directly related to the length of a container ship implying that it can range up to 400 m. The length of a quay is then influenced by the number of berths needed to simultaneously handle container ships. The width of a seaside could be up to 60 m. These would both enable the handling of the largest forthcoming container ships such as Triple E Maersk (see Table 4.3). In addition, the sea water in the terminal accessing channels and near berths enabling access and docking needs to be sufficiently deep (in the above-mentioned example at least 17 m). Experience so far indicates that the water depth in the main ports has been continuously improved in line with deploying large advanced container ships. If the depth is adopted to be 15 m as the required minimum, the number of appropriate ports has increased from 17 in 2000 to 25 in 2003,

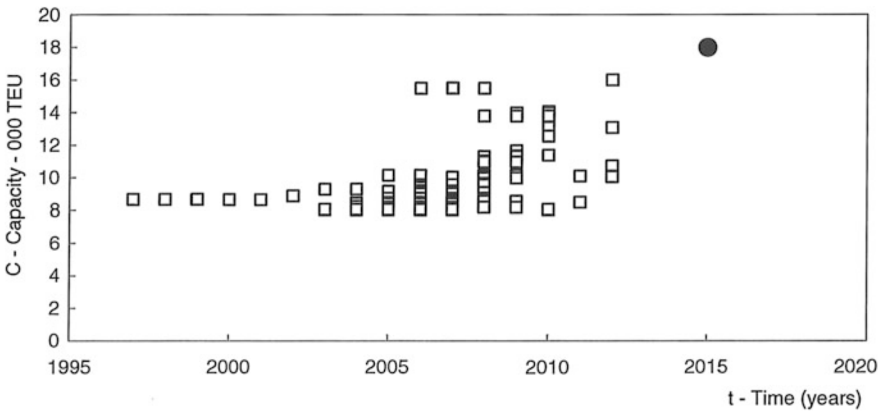


Fig. 4.10 Development of the capacity of large container ships (*period* 1997–2012) (http://en.wikipedia.org/wiki/List_of_largest_container_ships)

and to 28 in 2008. Consequently, the infrastructure of the main ports in the major trading regions in terms of the required water depth and length of berths is adequately provided for current and forthcoming large advanced container ships (Tozer 2001).

4.3.2.3 Technical/Technological Performances

Design

Large advanced container ships have been characterized by a persistent increase in size, capacity, and related engine power over time. Table 4.3 shows the milestones of such developments over the past 40 years.

In addition, Fig. 4.10 shows the general trend of increasing capacity of the 267 largest container ships over the past 15 years.

Three periods can be distinguished: the first (1997/2003) when only ships of a capacity of about 8,000 TEU were built, the second (2003/2005) when ships with a capacity of 8,000–10,000 TEU were built, and the last (2006–2012) when ships of a capacity between 8,000 and 15–16,000 TEU were built. The latest are usually called ULCS (Ultra Large Container Ships). One of them, the Triple E Maersk to be launched in 2015, will represent an advanced step in increasing the size to about 18,000 TEU/ship. However, the capacity of these ships in terms of TEU and DWT does not reflect the standard rule of 14 DWT/TEU as mentioned in Table 4.2, but rather less: from 9.9 DWT/TEU for the largest (Triple E Maersk) to 11.0 DWT/TEU to the smallest (2,800 TEU) container ship. This indicates that they are actually designed assuming that all TEUs on-board will never be completely full.

Advanced container ships have been designed for relatively constant "design" conditions. Such conditions have mainly influenced the hull form, rudder and propeller design, size, and power of the main engine, and the capacity and layout of auxiliary systems. Consequently, designing of future large advanced container

ships will have to be flexible in order to be adaptable to both "design" and "off-design" conditions. The former conditions are characterized by increased resistance of the hull due to operating at higher "design" speed(s), which compromises their overall energy, economic, and environmental efficiency. The latter conditions imply operating at lower than design speeds, i.e., slow steaming, which reduces fuel consumption and improves economic and environmental efficiency. In order to avoid the negative effects of changing conditions, future large advanced container ships will have to be designed (particularly hull and propulsion system-engines) for a range of the most likely operating speeds and draughts, thus balancing between the two compromising effects: one for reducing the operating speed and the other for increasing the capacity.

For example, the forthcoming Triple E Maersk ship is designed with a wider hull in order to accommodate the specified 18,000 TEUs. Such a wider U-shaped hull creates higher propulsion resistance than the narrower V-shape hull of its closest counterpart—Emma's Maersk. However, the Triple E's operating speed is limited to 23 kts (two engines generate the required power of 65–70 MW while running at 80 rpm (revolutions per minute), while Emma's is limited to 25 kts (the single engine generates the required power of 80 MW while running at 90 rpm). Thus, despite operating at higher propulsion resistance, thanks to operating at a lower engine rate and operating/cruising speed, the Triple E Maersk is expected to be overall more efficient than its closest smaller counterpart Emma Maersk. Figure 4.11 shows the principal differences in design of the two ships.

However, in both cases, utilization of the ships' available capacity (deadweight) is variable mainly due to frequent oversupply on the one hand and fluctuating market conditions on the other. These conditions which will likely become increasingly common in the future.

Propulsion/engines and propellers

Propulsion system/engines

The propulsion system/engines of large advanced container ships are one of their crucial components. Some empirical evidence indicates that their power can be roughly estimated from the modified Admiralty formula as follows:

$$P = c_p * V^{3+k} * \Delta^{2/3} \tag{4.4}$$

where
c_p is the coefficient
V is the ship's designed operating speed (kts); and
Δ is displacement (tons).

The displacement (Δ) is the actual gross weight of the ship consisting of its own empty weight and the weight of its cargo, fuel, fresh water, provisions, and crew. As can be seen, the propulsion power is proportional to the ship's speed (V) to the power of $3 + k$ and to its displacement to the power of 2/3. By proper selection of

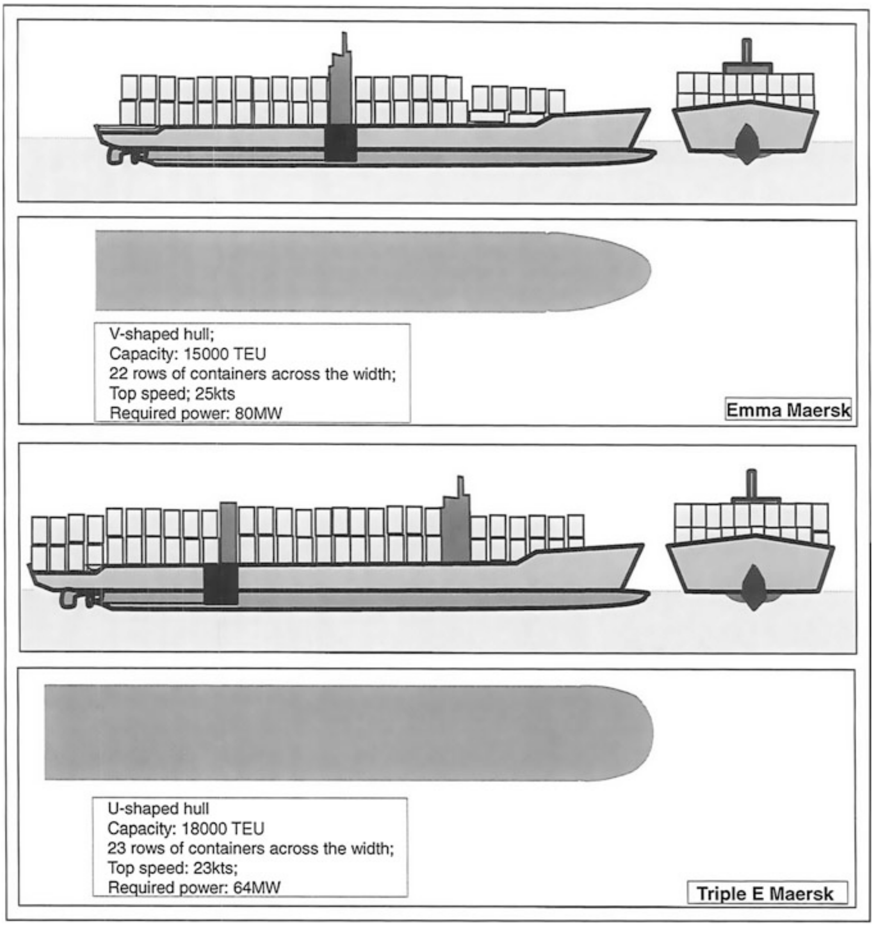


Fig. 4.11 Scheme of large advanced container ships

the coefficients (c_P) and (k), each individual speed–power curve of each individual ship can be expressed. In addition, Eq. 4.4 suggests that more engine power efficiency can be obtained by increasing the ship's size than by increasing the ship's speed (DNV 2012). Figure 4.12 shows the relationship between the size and engine power of large container ships.

In this case, the engine power increases at a decreasing rate as the ship's size increases, thus confirming the above-mentioned trend of designing larger container ships assumed to operate at lower speeds. The exception is the forthcoming Triple E Maersk as the largest container ship in the world with a capacity of 18,000 TEU and two engines delivering about 65 MW of power as compared to its currently largest counterpart (Emma Maersk) with a capacity of 15,000 TEU and a single engine delivering 67.7 MW of power (i.e., 3.61 vs. 4.51 kW/TEU, indicating an improvement of the power efficiency of about 25 %) (Table 4.3).

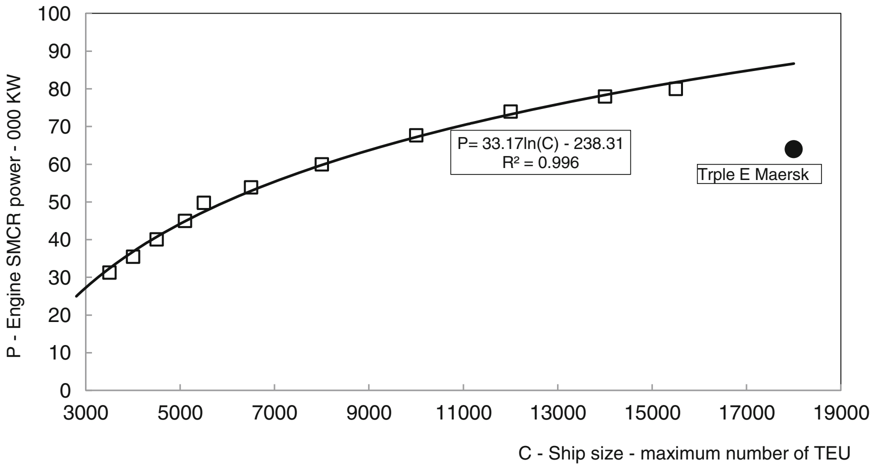


Fig. 4.12 Relationship between engine power and size (carrying capacity) of large advanced container ships (*SCMR* Specific Maximum Continuous Rating) (MAN Diesel 2011)

Propellers

The propulsion system of large advanced container ships is usually placed near the middle of the ship in order to make the best use of the rigidity of the hull and to maximize the carrying capacity. Once the main propulsion system is made available, the crucial element to be designed is the propeller. Propellers of existing container ships are made of nickel aluminum bronze usually with six blades. Their diameter and weight generally increase at a decreasing rate as the engine SMCR (Specific Maximum Continuous Rating) power for the specified speed increases. For example, for an engine of 60 MW SMCR power, the diameter of a propeller rotating at the speed of 94 r/min is about 9.2 m and its weight 95 tons. For an engine of 100 MW SMCR power rotating at the same speed, the diameter is about 10 m weighing 155 tons. For engines of 60 MW SMCR power rotating at the speed of 104 r/min, the diameter is about 8.5 m and weight 90 tons. For an engine of 100 MW power rotating at the same speed, the diameter is about 9.7 m and weight about 140 tons. This indicates that higher rotating speeds enable the design and construction of propellers with smaller diameter and weight (MAN Diesel 2011). For example, the forthcoming Triple E Maersk container ship will be equipped with a twin engine/twin screw propulsion system. Each of the two propellers will have a diameter of 9.8 m and 4 blades as compared to the Emma Maersk ship equipped with a single engine/single screw propulsion system where the propeller has a diameter of 9.6 m and 6 blades. In the twin screw propulsion system, the propellers are lighter, thus reducing any vibration of the hull. In addition, such systems provide greater pushing power and lower water resistance (Tozer 2001).

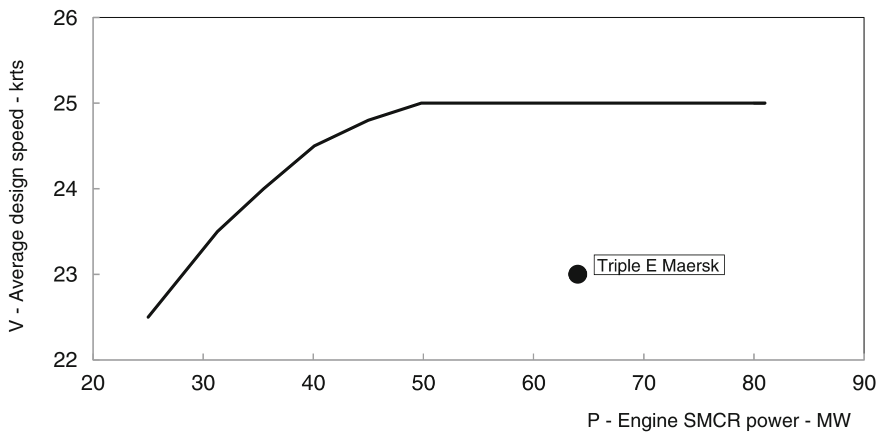


Fig. 4.13 Relationship between the design speed and the engine power of large advanced container ships (*SCMR* Specific Maximum Continuous Rating) (MAN Diesel 2011)

4.3.2.4 Operational Performances

The operational performances of large advanced container ships include speed, maneuverability, turnaround time, technical productivity, and fleet size/capacity.

Speed

Design speed

The design speed of large advanced container ships generally increases as the engine power increases, albeit at a decreasing rate. Since the engine power increases with the size of the ship, the speed also tends to increase in line with the size of the ship. However, it remains constant and independent of the size of the ship and related engine power in ships larger than 5,500 TEU and with an engine power equal or greater to about 50 MW; the latter is shown in Fig. 4.13.

However, the most recent exception from the above-mentioned rule of thumb is the largest Triple E Maersk container ship expected to be launched in 2015, with a design speed of 23 kts and a total twin-engine power of about 645 MW.

Operating/cruising speed

The operating/cruising speed of large advanced container ships differs in practice from their design speed due to the various reasons. One of these reasons is the preference of operators to minimize fuel consumption and related costs by adopting lower speeds. As a result, four speed categories of these ships can be distinguished as follows:

- Nominal speed (20–25 kts; 37.0–46.3 km/h), which represents the optimal cruising speed at which a given container ship and its engine have been designed to operate;
- Slow steaming speed (18–20 kts; 33.3–37.0 km/h), which represents the speed achieved by running the ship's engines below their capacity in order to reduce fuel consumption. (In 2011, more than 50 % of the global container shipping capacity was operating at this speed);
- Super slow steaming speed (15–18 kts; 27.8–33.3 km/h), which is also known as the economic speed aiming at minimizing fuel consumption while still maintaining a competitive commercial service; and
- Minimal cost speed (12–15 kts; 22.2–27.8 km/h), which represents the lowest technically possible speed since even lower speeds do not lead to any significant additional reduction in fuel consumption. (However, since these speeds and the related quality of services are commercially unviable, it is unlikely that maritime shipping companies will adopt them as part of their practice).

The practice of slow steaming emerged during the financial crisis of 2008–2009 when on the one hand, the demand for international trade and containerized shipping was severely affected, and on the other the new capacity ordered during the previous years of economic boom was coming into service (Figs. 4.9, 4.10). In reaction to such an imbalance between the decreased demand and increased capacity, maritime shipping companies adopted slow steaming and even extra slow steaming services on particular routes. Since the lower operating/cruising speeds required longer ship turnaround times, more ships were needed and indeed were available thanks to the new additional capacity.

It seems that slow steaming will remain the operational practice of many shipping companies due to the following reasons: (i) reducing fuel consumption and related costs, particularly if the trend of increasing fuel prices continues; and (ii) reducing emissions of GHG, thus respecting increasingly stricter environmental regulations.

As an innovative operational practice/regime, slow steaming will require adapting engines through their "de-rating," namely involving the timing of fuel injection, adjusting exhaust valves, and exchanging other mechanical components to the new speed and power level of about 70 % instead of the previously regular 80 %.

Maneuverability

One additional important operational advantage of large advanced container ships is their maneuverability. Conventional container ships of all sizes generally satisfy all of the IMO (International Maritime Organization) maneuverability criteria by using conventional steering systems. Some problems emerge around congested ports as the wind loading on the above-water profile of large units can be great. Therefore, for example, on the currently largest Emma Maersk container ship, two bow and two stern thrusters provide port maneuverability, and two pairs of stabilizer fins reduce rolling. When the banking angle is 20°, the bridge sways by

about 35 m. In addition, the turning diameter of the ship operating at the speed of 24 kts (44.5 km/h) is about 0.81 nm (i.e., 1.5 km).

Turnaround time

The turnaround time of a large container advanced ship scheduled to operate along a given route is defined as the total round time between the given origin and destination port, and back. This time includes the ship's turnaround time at the origin and destination port, its stop/transit time at the intermediate ports (which usually depends on the pattern and volumes of freight demand to be served in both directions), and the operating/cruising time between the particular ports. Thus, the ship's route between each given origin and destination port can be considered to consist of several segments. If the stops are the same in both directions, the turnaround time of a given ship can be estimated as follows:

$$\tau_{tr} = \tau_0 + 2 * \left[\sum_{i=1}^{N} \tau_i + \sum_{k=1}^{K} \tau_k \right] + \tau_d \tag{4.5a}$$

where

τ_o, τ_d is the ship's turnaround time at the origin and destination port, respectively (days);
τ_i is the ship's operating/cruising time along the (i)-th segment of a given route (days);
τ_k is the ship stop/transit time at the (k)-th intermediate port along a given route (days);
N is the number of segments of a given route; and
K is the number of ports along a given route where the ship stops ($K = N - 1$).

The ship's operating time along the (i)-th segment of the route in Eq. 4.5a can be estimated as follows:

$$\tau_i = s_i / V_i \tag{4.5b}$$

where

s_i is the length of the (i)-th segment of the route (nm); and
V_i is the ship's operating/cruising speed along the (i)-th segment of the route (kts)

In addition, the length of the route in one direction can be estimated as follows:

$$d = \sum_{i=1}^{N} s_i \tag{4.5c}$$

where all symbols are as in the previous equations.

It follows from Eq. 4.5a that reducing the cruising speed increases the ship's turnaround time along a given route, which can be partially compensated by shortening its turnaround time at the origin and destination port, and the stop/

transit time(s) at intermediate ports. These times generally depend on the ship's size, volume of load/cargo, and the rate of ship/container handling, the latter influenced by the available (increasingly automated) loading/unloading facilities and equipment at ports (Tozer 2001).

In order to estimate the performance of the additional loading and unloading facilities and equipment in ports (cranes) needed to compensate the extra travel time due to slow steaming, Eq. 4.5b can be modified as follows:

$$\tau = s * (1/v_s - 1/v_r) \tag{4.5d}$$

where

C is the ship's capacity (TEU);

S is the length of route, i.e., trip distance between origin and destination port (nm);

v_r, v_s is the regular and slow steaming speed, respectively (kts).

Equation 4.5d states that the ship's extra trip time will increase in line with the route length and the difference in the regular and the slow steaming speed. Such trip time extensions generally increase the cost of TEU/goods time while in the chain, which can be estimated as in Eq. 3.1a (Chap. 3) as follows:

$$\Delta c = \beta * C * s * (1/v_s - 1/v_r) \tag{4.5e}$$

where

Δc is the extra cost of freight/goods time ($US/TEU-h);

β is the freight/goods time while in transportation ($US/TEU-h).

The other symbols are analogous to the previous equations. The extra trip and cost of freight/goods can be partially compensated by shortening the ship's loading/unloading time at the origin/destination port, respectively. Modifying Eq. 3.1a (Chap. 3), the time loading units remain in the regular and the slow steaming supply chain can be estimated, respectively, as follows:

$$\tau_r = 2C/n_r * \alpha_r + s/v_r \text{ and } \tau_s = 2C/n_s * \alpha_s + s/v_s \tag{4.5f}$$

where

n_r, n_s is the number of loading/unloading facilities and equipment (cranes) at the origin and destination port serving regular and slow steaming ships, respectively (-); and

α_r, α_s is the service rate of a single facility (crane) in either port serving a ship operating under regular or slow steaming regime (TEU/h).

The other symbols are analogous to those in the previous equations. Consequently, the loading/unloading capacity for a slow steaming ship that could compensate the extra cruising time can be estimated from Eq. 4.5e as follows:

$$n_s\alpha_s = \frac{2C * n_r * \alpha_r}{2C - n_r * \alpha_r * s * (1/v_s - 1/v_r)} > 0 \tag{4.5g}$$

This is reasonable only if the denominator of Eq. 4.5g is positive, i.e., if the reduced speed is not less than:

$$v_r > \frac{n_s * \alpha_s * v_r * s}{v_r * C + n_r * \alpha_r * s} \tag{4.5h}$$

Equation 4.5h states that compensating the ship's extra trip time due to slow steaming by increasing the loading/unloading capacity at ports (i.e., shortening the corresponding time(s)), could be achieved only if the reduced speed is not under a certain threshold. Otherwise, this is not possible, thus forcing users/freight/goods shippers to adapt and accept such changed quality of service.

Technical productivity

As with other vehicles, the technical productivity of a large advanced container ship can be determined as the product of its operational/cruising speed and carrying capacity as follows:

$$TP = V * C(d) \tag{4.5i}$$

where

C(d) is the capacity of a given container ship operating along the route *d* (DWT or TEUs).

The other symbols are as in the previous equations.

The technical productivity of a given route for a given period of time (week, month, year) can be estimated as the product of the technical productivity of a single ship and the service frequency. In many cases, it is assumed that all services are carried out by ships of the same capacity operating at the same speed. The service frequency is directly proportional to the quantity of freight to be transported (TEUs) and inversely proportional to the ship size and its load factor (Chap. 2).

Fleet size/capacity

The fleet size/capacity of large container shipping companies can be expressed as the sum of the capacity of all ships in the fleet. Figure 4.14 shows the relationship between the total fleet capacity expressed in TEUs and the number of ships in the fleet for the 20 largest global container shipping companies.

As can be seen, the total transport capacity expressed in TEUs increases in line (at a constant rate) with the number of ships in the fleet. The average capacity of a container ship in a fleet in the given example is about 4,000 TEU.

The number of ships in the fleet of large advanced container ships operating on the route *(d)* during the time period *(T)* can be determined, based on Eq. 4.5a, as follows:

$$N(d,T) = f(T,d) * \tau_{tr} \tag{4.6}$$

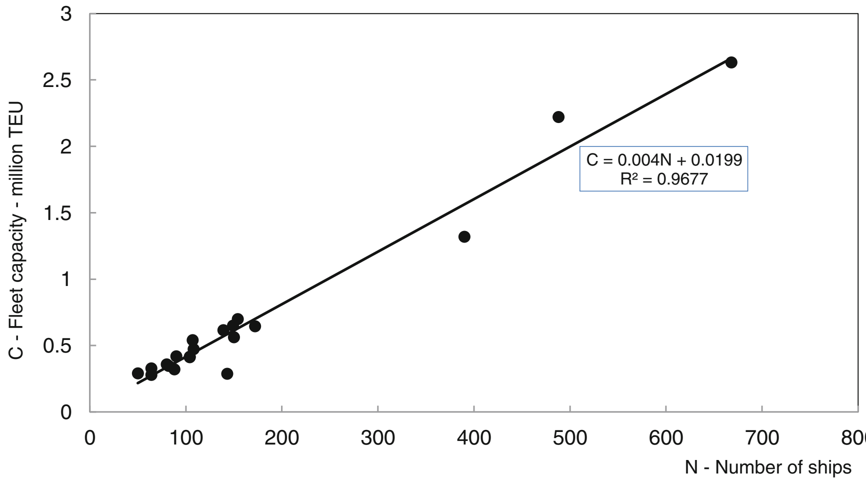


Fig. 4.14 Relationship between the size and capacity of the containership fleet (May 2012) (http://en.wikipedia.org/wiki/Intermodal_freight_transport)

where

f(T, d) is the service frequency on the route *(d)* during time *(T).*

The other symbols are analogous to those in the previous equations.

Equation 4.6 confirms that increasing the ship's turnaround time due to slow steaming will require a larger fleet of ships of a given size. As the volumes of freight demand increase, so does the number of ships of a given capacity and utilization in the fleet. At the same time, using larger and better utilized ships will require fewer of them.

4.3.2.5 Economic Performances

The economic performances of advanced large container ships include their costs and revenues.

Costs

The costs of container ships, as the costs of other categories of freight/goods transport vehicles, consist of capital and operating cost including the cost of capital, port and terminal call charges, costs of insurance, maintenance and repair, costs of lubes and stores, and fuel, crew, and administration/overhead costs. Experience so far shows that due to economies of scale, the average cost per transported unit of freight/goods (TEU) on a given distance/route decreases more than proportionally as the size of a container ship increases. Figure 4.15 shows an

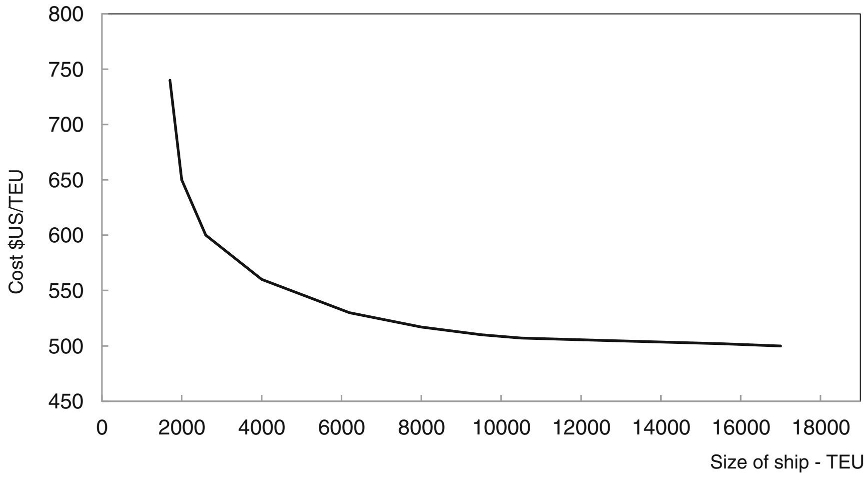


Fig. 4.15 Relationship between the average cost per TEU and the size of container ship (AECOM 2012; Cullinane and Khanna 2000; Nottebon and Rodrigue 2007; Tozer 2001)

example for a Transatlantic route of an average length of about 4,000 nm (AECOM 2012; Nottebon and Rodrigue 2007).

Such diminishing economies of scale pose the question whether large advanced container ships such as the Triple E Maersk will bring more substantial cost-decreasing benefits as compared to their smaller predecessors. In all cases, fuel costs dominate (80–85 %), followed by capital costs (about 8.0 %), Panama Canal tolls (6–10 %), and crew costs (1.2–2.4 %) (AECOM 2012). In addition, for a given ship size, the average unit cost increases in line with the route length and the operating/cruising speed, both approximately at a decreasing rate. The latter is because the increased speed requires greater fuel consumption, thus additionally raising the share of already dominating fuel costs in the total operating costs of the ship.

Revenues

The revenues of container ship operators come from transporting containers between ports.

Usually, their rates are set to cover operating costs while respecting highly competitive market conditions. Since these conditions are all quite different, the rates vary substantially across operators, markets and routes, and prevailing micro- and macroeconomic conditions. In addition, they depend on the transport distance and sometimes also ship size. In addition, generally speaking, the exporting rates when ships are fuller are lower than those of returning trips when ships may transport only empty containers. An example of such high diversity of the average unit rates in container shipping is shown in Fig. 4.16.

In the specified month, the average rate for transporting freight/goods of 1 TEU generally increased in line with the port-to-port distance in all markets, except

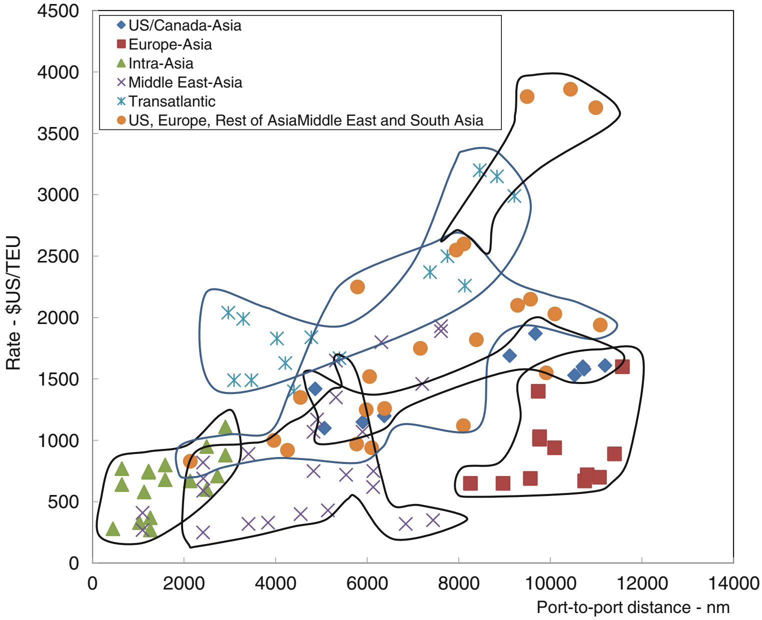


Fig. 4.16 Relationship between the lowest rate and port-to-port distance for transporting containers in particular markets—(March 2010) (DSC 2010)

Europe–Asia, US/Canada–Asia, and partially Middle East-Asia markets. In these markets, the rates remained rather independent of the distance, but very distinctive across the particular routes. All rates were changed the following month, thus indicating their above-mentioned high fluctuation depending on the short-term market and stakeholder-related conditions (DSC 2010).

4.3.2.6 Environmental and Social/Policy Performances

The environmental and social/policy performance factors of large advanced container ships are considered to be the energy/fuel consumption and related emissions of GHG (Green House Gases), land use/take for the container terminals in ports handling such ships (environmental), as well as traffic incidents and accidents (safety) (social).

Fuel consumption and emissions of GHG

Fuel consumption

Large advanced container ships consume MDO (Marine Diesel Oil), sometimes also known as No. 6 Diesel or HFO (Heavy Fuel Oil) or Bunker C fuel adapted to the 2005 standards as MDF (Marine Distillate Fuels) (http://en.wikipedia.org/wiki/

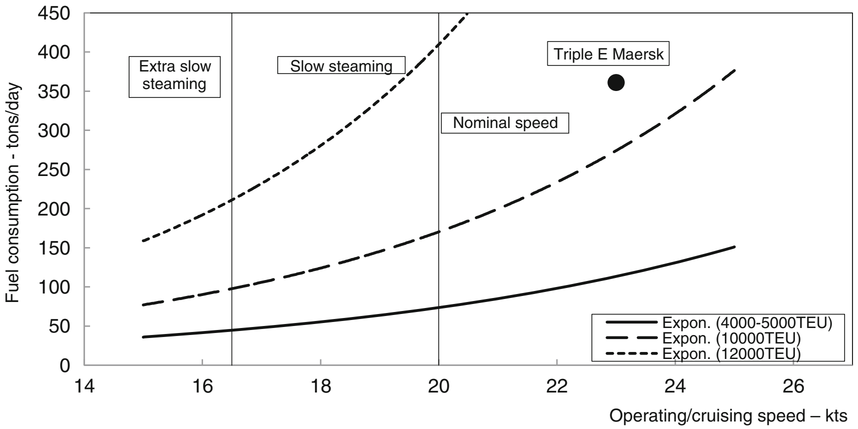


Fig. 4.17 Relationship between the fuel consumption and the operating speed and size of container ships (AECOM/URS 2012; Churchill and Johnson 2012; Notteboom and Carriou 2009)

Heavy_fuel_oil). These are largely unrefined very thick crude oil derivatives, often needed to be heated by steam in order to reduce their viscosity and thus enable them to flow. The fuel consumption of large container ships generally depends on their size and operating speed and usually increases in line with both factors individually and/or simultaneously as shown in Fig. 4.17.

As can be seen, the fuel consumption of a container ship of a given size increases more than proportionally as the operating/cruising speed increases. For example, large container ships of a capacity of 12,000 TEU such as Emma Maersk consume about 400 tons of fuel per day while cruising at a speed of about 20 kts (the length of route is about 15,000 nm) (AECOM/URS 2012). Ships with a capacity of 10,000 TEU consume about 375 and 200 tons of fuel per day while cruising at the (designed) speed of 25 kts and reduced speed of 21 kts, respectively. For container ships of 4,000–5,000 TEU, the corresponding fuel consumption is 150 and 85 tons per day, respectively. The forthcoming largest Triple E Maersk ship of a capacity of 18,000 TEU will consume about 360 tons of fuel per day while cruising at the speed of 25 kts. These figures illustrate the very high sensitivity of fuel consumption to changes in the ship's operating/cruising speed.

In addition, fuel consumption can be expressed in other units. For example, currently the world's largest single diesel Wärtsilä-Sulzer 14RTFLEX96-C engine powering the Emma Maersk largest container ship delivers the maximum power of 80–81 MW for the designed cruising speed of 25 kts. Under such regime it consumes about 19,000 l or 16.7 tons of HFO/h or 198 g/KWh. The forthcoming Triple E Maersk container ship with two MAN diesel engines delivering total power of 64 MW enabling an operating/cruising speed of 23 kts will consume 15.04 tons of HFO/h, or about 231 g of HFO/kWh. At the designed operating/

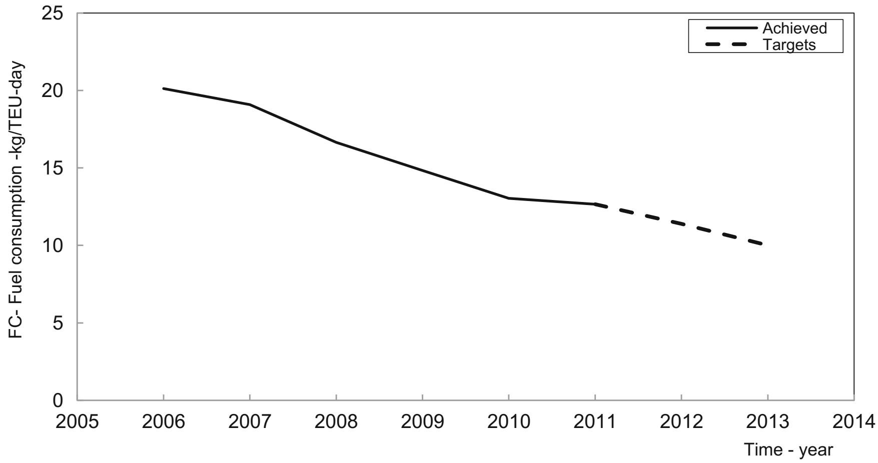


Fig. 4.18 Changes in the average unit fuel consumption of a large shipping company over time—Maersk Line (Maersk Line 2011)

cruising speeds, these give 1.39 kg of HFO/TEU/h for Emma Maersk and 0.84 kg of HFO/TEU/h for Triple E Maersk ship, which is a reduction of about 40 % (MAN Diesel 2011; Tozer 2001).

Endeavors to reduce fuel consumption

Modern large advanced container ships use HFO (Heavy Fuel Oil), the burning of which produces GHG such as SO_x (sulfur oxides), NO_x, (nitrogen oxides), PM (particulate matter), and CO_2 (carbon dioxide). Therefore, due to the permanent increase in the total emissions of GHG, the maritime industry and its national and international organizations have made efforts to at least control such emissions. For example, the WSC (World Shipping Council) and its members have been engaged through the IMO (International Maritime Organization) in numerous efforts to improve the energy efficiency of the maritime sector through reducing the ships' fuel consumption and related emissions of GHG. At the level of individual shipping companies, this has been carried out through medium- to long-term sustainability plans. Figure 4.18 shows the achievements of a large shipping company—Maersk Line—over the 2006–2011 period.

As can be seen, the company has certainly followed a downward path toward the established target of an average fuel consumption of about 10 kg/TEU/day to be achieved by 2013. This also implies corresponding savings in the emissions of GHG.

Other efforts have been institutionalized through Annex VI of MARPOL, an international treaty developed through the IMO, which has established legally binding international standards for regulating the energy efficiency of existing and future ships. Consequently, the main environmental and social/policy performances of large advanced container ships are contained in these standards

specified by the MEPC (The Marine Environment Protection Committee) of the IMO (International Maritime Organization) aimed at reducing the energy consumption and related emissions of GHG (Green House Gases) over the forthcoming 2013/14–2025 period and beyond (the standards are also specified for all other types/categories of ships). The main quantitative attributes of these standards for container ships with a deadweight of over 15000 tons imply the following targets for reducing GHG (CO_2) emissions: Phase 0–0 % over 2013–2014; Phase 1–10 % over 2015–2019; Phase 2–20 % over 2020–2024; and Phase 3–30 % beyond 2025 (MEPC 2012). This is expected to be achieved by: (i) technical/technological measures; (ii) operational measures; and (iii) economic measures.

- **Technical/technological measures**

The technical/technological measures aim at enhancing the energy efficiency of large advanced container ships through improving their technical/technological performances. For existing ships, this can be carried out through different modifications. For new ships, this is to be carried out through their design. Some of these measures include:

– Reducing propulsion resistance by modifying the hull form;
– Ensuring enhanced propulsion efficiency by modified propeller(s);
– Increasing the hull size in order to increase the deadweight (capacity);
– Using energy from exhaust heat recovery; and
– Using renewable energy (wind, solar power, etc.).

EEDI (Energy Efficiency Design Index): This index is proposed by the IMO in order to evaluate the effects of the particular above-mentioned technical/technological measures for existing and new ships. In general, the rather complex expression for the original EEDI can be simplified as follows (IMO 2011; LR 2011):

$$\mathrm{EEDI_{ref}} = \frac{P * \mathrm{SFC} * C_f}{\mathrm{DWT} * V}\,(\mathrm{gCO_2/ton-mile}) \tag{4.7a}$$

where

P is the engine power including the main engine and auxiliary engines (kW);
SFC is the specific fuel consumption (the recommended value is 190 g/kWh)
C_f is the carbon emissions factor (3.1144 gCO_2/g of fuel for HFO);
DWT is the ship's deadweight (tons); and
V is the speed that can be achieved at 75 % of P of the main engine.

As indicated in Eq. 4.7a, EEDI decreases more than proportionally as the ship's deadweight *DWT* and operating/cruising speed V increase, and increases in proportion with the engine power P and fuel efficiency *SFC*.

Using the data for container ships built over the period 1999–2008, the average EEDI is calculated and regressed with the deadweight DWT. The average regression line is obtained as follows (Flikkema et al. 2012; IMO 2011):

$$EEDI_{ref} = 174.22 * DWT^{-0.201} \tag{4.7b}$$

where all symbols are as in the previous equations.

This Reference Line is used as the terms of reference for existing and especially new-build ships. If the attained EEDI value of a given ship is above the Reference Line, the ship is considered energy inefficient, and vice versa. Consequently, the required EEDI can be defined as the allowable maximum attained EEDI for a given container ship, which is below and/or at most at the Reference Line. Regarding the above-mentioned policy targets for improving the energy efficiency of container ships over the forthcoming period (i.e., by 2025 and beyond), the required EEDI can be estimated as follows (IMO 2011):

$$EEDI_{req} = (1 - X/100) * EEDI_{ref} \tag{4.7c}$$

where

X is the target for improving the energy efficiency of container ships during the specified period of time (%).

As an example, using Eq. 4.7a, the attained EEDI is calculated for existing Post-Panamax large container ships which entered service over 2003–2008. Capacity utilization (DWT) is assumed to be 70 %, the power 75 % of the maximum engine power, and the speed 1 kts below the maximum designed speed (MAN Diesel 2011). The required EEDIs respecting the above-mentioned energy efficiency improvement targets can be calculated using Eqs. 4.7b, c. Figure 4.19 shows the results. As can be seen, all considered container ships fulfill the required 2013–2014 EEDI. Ships larger than 85,000 DWT will be able to satisfy the required 2015–2019 EEDI. None of these ships will be able to satisfy the required 2020–2024 EEDI, or those set for 2025 and beyond.

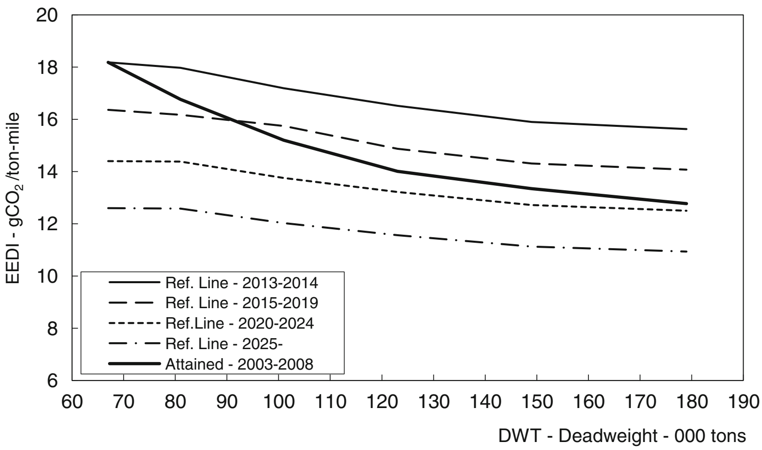


Fig. 4.19 Environmental performances of the large advanced container ships—relationship between the existing and required EEDI, and the capacity (IMO 2011; MAN Diesel 2011)

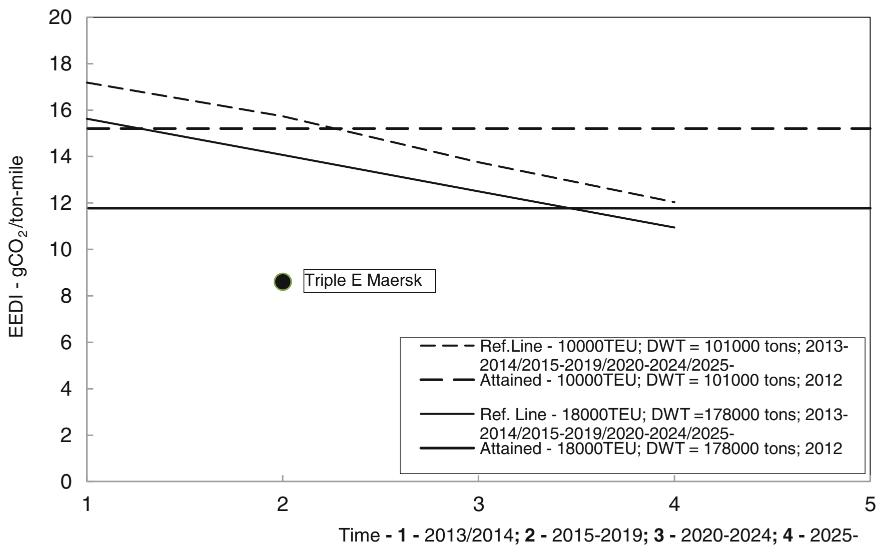


Fig. 4.20 Environmental performances for the selected large advanced container ships—attained and required EEDI specified by the MEPC policy for the 2013–2025 period and beyond

In addition, Fig. 4.20 shows that container ships larger than 85,000 DWT including the largest forthcoming Triple E Maersk to be launched in 2015 will be able to satisfy the required EEDI from 2012 until 2020 and slightly beyond, but not later. If, however, the Triple E Maersk ship is to be designed as expected (SFC = 168 g/kWh and engine power $P = 65$ MW), its attained EEDI will be comfortably below the required EEDI over the entire period (2015–2025 and beyond).

- **Operational measures**

Operational measures aim at improving the energy efficiency of large advanced container ships through innovative operations. They can be applied to existing ships by shipping companies in the scope of their efforts to improve energy and consequently economic efficiency. Some of these measures include:

- Optimizing operations of individual ships and fleets;
- Operating/cruising at reduced speed, i.e., slow steaming;
- Entering and leaving ports on time;
- Maintaining the hull clean in order to reduce propulsion resistance; and
- Ensuring regular maintenance of the ship's overall machinery.

In order to promote, stimulate, and implement some and/or all above-mentioned operational measures applicable to existing large advanced container and all other ships, the IMO has also proposed two indicators/tools: EEOI (Energy Efficiency Operational Indicator) and SEEMP (Ship Energy Efficiency Management Plan).

EEOI (Energy Efficiency Operational Indicator): This indicator was introduced on a voluntary basis in 2005 and is expected to be used by the owners and operators of large advanced container and other ships as an indicator expressing the energy efficiency of a given ship in operation. It can be estimated as follows (IMO 2012):

$$\mathrm{EEOI} = \frac{\mathrm{FC} * C_f}{W_c * d} (\mathrm{gCO_2/ton - mile}) \quad (4.7d)$$

where
FC is the fuel consumption during a trip (tons);
W_c is the actual weight of freight/goods (tons); and
d is the length of route, i.e., actual trip distance (nm).

The other symbols are analogous to those in the previous equations.

Equation 4.7d indicates that EEOI is proportional to the fuel consumed during a given trip and is inversely proportional to the actual weight of freight/goods on-board and length of route. Thus, the EEOI can be improved by decreasing the fuel consumption, as mentioned above, through reducing the operating/cruising speed, i.e., slow steaming, while transporting larger quantities of freight on longer distances.

Despite being expressed in the same units as EEDI, the EEOI is estimated from the values of particular variables measured during or just after a given trip. Therefore, it can be used for measuring changes in the energy efficiency of the same ship operating along different routes/markets under different conditions. Due to such inherent diversity of the independent variables already used for the same ship, the EEOI appears inappropriate for the comparison of different ships.

SEEMP (Energy Efficiency Management Plan): This management plan is used for implementing improvements in the ship's and fleet's energy efficiency through operational measures. These include planning the trip in terms of weather routing, arrivals and departures from ports on time, optimization of speed, etc., optimizing the ship's handling and maintenance of the hull, use of engines and waste heat recovery, as well as energy management and reporting. The implementation of SEEMP voluntarily by ship and fleet owners and/or operators can be carried out through five procedures comprising the energy efficiency improvement cycle as follows (Sala 2010):

- *Planning* identifies measures for improving energy efficiency, sets up the targets, defines the activities and persons in charge, and establishes all these as a system with a roadmap over a 3–5 year period;
- *Implementation* implies realization of the energy efficiency improvements according to the plan; these include zero or low cost simple improvements made during daily operation and maintenance, less than 2 year pay-back improvements of systems by minor conversions during regular operations, and improvements of the systems and haul requiring the ship to dock;

- *Monitoring* implies developing the method and performing energy efficiency monitoring continuously by collecting and processing quantitative information/data during and/or at the end of the improvement cycle; and
- *Self-evaluation* implies assessing the effects of the implemented measures by using the monitored results and feeding them back to the next energy efficiency improvement cycle; and
- *Publication* of the results voluntarily implies presenting the results to the professional public and enabling third party evaluation.

Due to the need for collecting a relatively large quantity of information even for a single trip, different support systems are being developed for calculating, analyzing, and preparing reports on energy efficiency improvement cycle(s).

- **Economic measures**

Economic measures aim at promoting and implementing the above-mentioned technical/technological and operational measures. IMO has proposed several measures classified into two broad categories as follows:

- The fuel pricing system (proposed by Denmark); and
- The emissions trading system (proposed by Norway, Germany, and France).

The former measure implies automatically charging an amount on the purchase of fuel. The collected funds would be used for different projects aiming at reducing emissions of GHG, particularly those in developing countries. In addition, a part of the amount collected would be awarded back to ships achieving substantial improvements in energy efficiency. The latter implies that the total amount of GHG generated by the shipping industry would be regulated by the emission trading system. In such a case, each ship would be assigned a credit in terms of the annual allowable emissions of GHG (CO_2). Subsequently, the differences between the actual and credited (assigned) emissions would be traded with other ships and/or the rest of the transport and other non-transport sectors.

Potential impact on global emissions of GHG

The presented EEDI and SEEMP measures are expected to significantly reduce emissions of GHG from the world's freight ships over the long-term 2010–2050 period. Figure 4.21 shows one such scenario.

As can be seen, both EEDI and SEEMP will contribute to reducing the total emissions of GHG (CO_2) as compared to the emission levels in 2010. For example, the reduction will be between 13–23 % over the 2020–2030 period. However, these measures will not be able to prevent a further increase in the total emissions of GHG according to an upward trend although with some reduced rates as compared to the BAU (Business As Usual) scenario, mainly driven by the expected growth in global trade.

The contribution of EEDI and SEEMP will most likely be proportional to the product of their share in the total global freight ship fleet and the above-mentioned

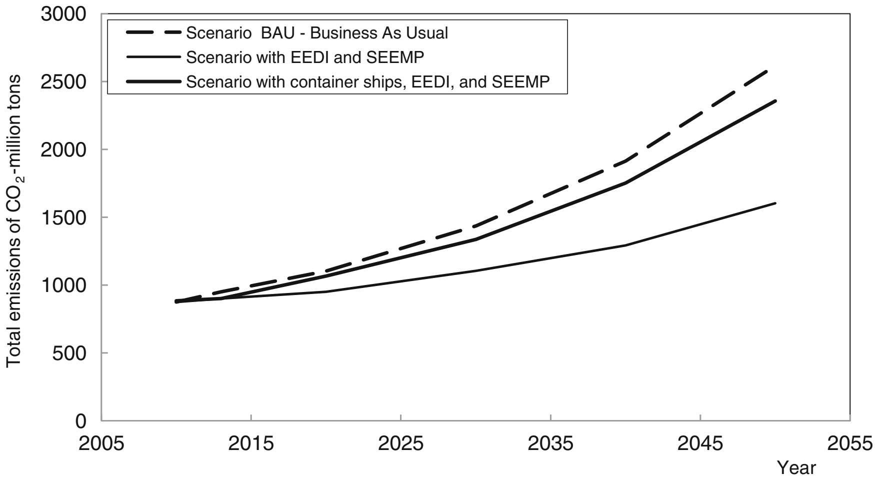


Fig. 4.21 Scenarios of development of emissions of GHG (CO_2) by the global freight ship fleet over time (IMO 2011; MEPC 2012)

required EEDI targets. In addition to the required EEDI targets, let the "what-if" scenario assume an increase in the share of large advanced container ships in the global fleet at an average rate of 5 %/10 years by 2050. This will amount to shares in the corresponding totals of 5, 7, 17, 23, 28, and 33 % in 2010, 2013, 2020, 2030, 2040, and 2050, respectively. As applied to the total amount of emissions of GHG, this again produces an upward trend as shown in Fig. 4.21. As can be seen, the contribution to decreasing of the total emissions of GHG (CO_2) would be about 3–10 % over the observed period (2010–2050).

Future measures and technologies for mitigating emissions of GHG

The main drivers of design of future large advanced container ships will be conditioned by the strategic plans of shipping companies and environmental constraints aiming at:

- Improving economics by reducing the staff and increasing productivity;
- Increasing flexibility of services by modifying routes and networks, and ship deployment;
- Optimizing utilization of containers, i.e., securing return freight/goods volumes;
- Minimizing delays at ports; and
- Minimizing fuel consumption and related emissions of GHG (Green House Gases) by meeting the current and prospective energy efficiency regulatory requirements, i.e., required EEDI.

In particular, the options for minimizing fuel consumption and related emissions of GHG through ship design include: (i) Reduction of power; (ii) New technology for power generation; and (iii) Renewable fuel/energy primary sources.

- Reduction of power can generally be achieved by designing/developing the hull form, reducing the weight and power for the ship's own use, frictional and wind resistance, and improving the engine efficiency;
- New technologies for power generation include use of alternative fuels such as biofuels, LNG (liquefied natural gas), LH_2 (liquid hydrogen) and fuel cells; and
- Renewable fuel/energy primary sources include solar and wind energy.

In addition, an option for minimizing the fuel consumption and related emissions of GHG includes forthcoming trip support systems, one of which is "Sea-Navi." These are designed to support online optimization of the ship's routing respecting the shortest distance, weather, characteristics of the hull, and regime of engine operation, thus contributing to improving EEOI and SEEMP.

Reduction of power

Some achievements have already been made by reducing power. An example of using existing technologies is the Triple E Maersk container ship, which will consume about 35 % less fuel (HFO) and emit about 20 % less CO_2 per TEU as compared to today's most energy efficient container ships, and about 50 % less of both as compared to the industry average for container ships operating in the Asia–Europe market. Such energy efficiency of about 9 % will be partially achieved also thanks to an advanced energy efficient waste heat recovery system, the purpose of which is to reduce the engine's need for fuel and consequent emissions of CO_2. The system operates by capturing the heat and pressure contained in the exhaust gases and then using them to move turbines creating mechanical energy for operating an electrical generator.

In addition, a future container ship concept has been proposed by Odense Steel Shipyard Ltd. The reference case is the existing A-class Post-Panamax container ship of a capacity of 8,500 TEU, 109000 tons DWT, length 352 m, draught 15 m, the power of main engine 63 MV at 100 rpm, and design speed of 26.5 kts. In parallel with improving the main engine and propeller design, an innovative WIF (Water in Fuel), WHRS (Waste Heat Recovery System), and EGR (Exhaust Gas Recirculation) system aiming at improving the ship's energy efficiency would be introduced in four of five designs as shown in Table 4.4 (OSSL 2009).

The given cases indicate that de-rated engine power, modified propeller design and slow steaming, in combination with other systems (WHRS, WIF, and EGR), could improve the ship's energy efficiency in terms of energy consumption and related emissions of GHG (CO_2) by about 30 %.

Furthermore, some other advanced container ship designs with existing HFO may be promising. One of these is the new method of powering large freight ships developed by Gamma Light and Heavy Industries Ltd. The method implies that instead of placing diesel engines at the rear of the ship as is common, the sets of

Table 4.4 Improving performances through the design of advanced future container ships (OSSL 2009)

Performance	1	2	3	4	5
WHRS	No	Yes	Yes	Yes	Yes
WIF and EGR	No	Yes	Yes	Yes	Yes
Capacity (TEU)	8,500	8,500	8,500	8,500	8,500
Design speed (kts)	26.5	26.5	26.5	24.1	22.08
Engine (de-rated) power (MW)	63.0	62.6	58.3	40.9	31.4
RPM[1)]	100	94	94	78	76
Propeller					
Diameter (m)	8.9	9.2	9.2	9.2	8.8
Number of blades	6	6	6	6	6
Fuel consumption (HFO) (tons/day)	278	246	227	160	121
Emissions of GHG (CO_2) (tons/day)	866	766	707	498	377

RPM Rotations per minute; (*1*) A-class as built (reference design); (*2*) New engine, larger propeller diameter + WHRS, + WIF&EGR; (*3*) 2 + New propeller blade design, hull coating, and advanced rudder; (*4*) 3 + Lower steaming I; (*5*) 4 + New Engine, Smaller propeller diameter, new propeller blade design, hull coating, advanced rudder + Lower steaming II

diesel electric units are placed down the side and along the entire length of the ship, enabling much higher efficiency due to much reduced use of the available power and proportionally less fuel consumption while maneuvering. Such a constellation is expected to improve the nominal (present) energy efficiency of ship(s) by about 75 %.

New technologies

Biofuels are considered as alternative fuels. They include biodiesel/vegetable oils and biogas. The former is applied to FAME (Fatty Acid Methyl Ester), which can be used exclusively or as an ingredient of conventional HFO. Generally, it can be produced from oleaginous crops such as rapeseed, sunflowers, soy beans, palm oils, etc. The latter, also known as SNG (Substitute Natural Gas), can be produced with similar characteristics as LNG (Liquefied Natural Gas) allowing use in LNG engines. The primary source of biogas is organic waste and energy crops. It can be used by LNG engines and also fuel cells (UniCredit 2009).

LNG is also an alternative fuel, the main component of which is methane. It has come under focus mainly due to its CO_2 content which is about 20–25 % lower than that of HFO. Also, it can reduce emissions of SO_x (Sulfur Oxide) by about 90–95 % and NO_x to the level complying with IMO Tier III limits to be in effect from 2016. In addition, the price of LNG would be comparable to that of HFO. However, the tanks for storing LNG are much larger than those for storing HFO, thus requiring more space, which can compromise the ship's loading capacity. Nevertheless, this could be compensated by improved energy efficiency. The engines powering the ship would be the dual-fuel hybrid constructions enabling operation in both HFO and LNG mode. Some designs such as Quantum

(DNV—Det Norske Veritas) indicate that the EEDIs of large container ships using a mixture of LNG/HFO could be significantly lower than that required beyond 2025 (by about 30 %). In addition, particular attention needs to be devoted to the safety and reliability of LNG bunkering systems by excluding any spillage (GL 2012).

In principle, fuel cells convert chemical energy (for example contained in hydrogen H_2 and oxygen O_2) directly into electricity used for powering the ship's electromotor(s). Such direct conversion makes hydrogen fuel cells highly efficient. On container ships they are located inside the container units and they can be of the PEM (Polymer Electrolyte Membrane) type characterized by a high power density and flexible behavior in operation. As such, they enable optimization of power use on a case by case (trip) basis depending on the prevailing conditions. The NYK Super Eco Ship 2030 is an example of a future container ship that could alternatively be powered by fuel cells (UniCredit 2009).

Renewable fuel/energy primary sources

Wind energy was commonly used in maritime operations in the middle ages. One modern example is the MS Beluga SkySails ship developed by two companies—KiteShip and SkySails—and launched in 2007 (EC 2010b). The wind assisting system includes larger sails attached, for example, to the container ship, which pull the ship through the water by using high-altitude wind(s). Depending on the ship's size, the sails can have up to about 5000 m^2 of surface area. They are divided into compartments with compressed air keeping them rigid. Such sails are controlled by computer in addition to an autopilot system used to determine the optimal shipping route(s) depending on the weather (prevailing wind) conditions. In the given case, the wind energy is partially used as a means of assistance, since a diesel HFO engine still remains in place. The potential improvement in the ship's energy efficiency is estimated to be up to about 10–35 %.

In addition, solar and wind energy will be used exclusively and/or in combination with LNG for powering future large container ships. In such cases, both solar and wind energy will be harnessed by solar panels (or solar cells on foils) and sails, respectively, and then either directly converted into electricity and consumed or stored for later use. Table 4.5 gives a comparison of the existing MV NYK VEGA and future NYK Super Eco Ship using different power sources.

The future NYK Super Eco ship will be equipped with an LNG engine with about 30 % less power, but supported by about 5–13 % of renewable (solar and wind) energy. Both will enable improvement of the ship's energy efficiency by about 70 %.

Another example is the Aquarius Eco Ship designed by EMP (Eco Marine Power) from Fukuoka (Japan). The central component of the ship is the Aquarius MRE System based on EnergySail technology. This is a renewable energy platform also designed by EMP fitted with different renewable energy technologies incorporating solar panels and wind power devices, energy storage modules, and a positioning system. The first enable tapping wind and sun power while at sea or

Table 4.5 Main characteristics of existing and future advanced large container ships (NYK Line/MTI 2010)

Basic characteristics: 9000 TEU/25 kts	MV NYK VEGA (2006)	NYK Super Eco Ship (2030)
Length (m)	338	353
Weight (m)	45.8	54.6
Draught (m)	13.0	11.5
Engine type	Diesel engine (HFO)	Fuel cell (NLG)
Required power (MW)	64	40
Renewable energy (MW)	0	Solar: 1–2/Wind: 1–3
Emissions of CO_2 (g/TEU-mile)	195	62

even in the port. The second enable energy storing for eventual future use. The latter contributes to sailing optimization. The solar panels and wind devices are located in an array of rigid sails made of composites whose number and area depend on the required power compensated by the assisting LNG engine. Such rigid sails would be automatically positioned to best suit the prevailing weather conditions including being lowered and stored during inconvenient weather. In addition to the Aquarius MRE System, the future Aquarius Eco Ship would be equipped with other energy efficiency improving components such as an advanced electrical propulsion system and waste heat recovery technologies. A computer system will monitor and control operation of all above-mentioned components. Such combination of technologies could lead to improving the energy efficiency of Aquarius Eco Ship(s) by about 40 % (http://www.ecomarinepower.com).

Land use

Large advanced container ships are handled at the port's container terminals. Each terminal consists of water-side berths for ship docking, a large coastal area of land for the storage of containers, specialized berth cranes and yard cranes for container loading/unloading to/from the ship and within the storage area, tractors and other equipment for handling containers from the ships to the storage area, gates for inland road trucks, in many cases yards, and barges and various maintenance and administrative buildings. The size of this used land generally increases proportionally or more than proportionally as the number and size of berths increases, as shown in Fig. 4.22 (an example for seven U.S. port container terminals). In addition, most ports set aside 'land banks' for future expansion, which can range from a few hundreds to a few thousand percent of the land occupied by existing terminals (CGI 2007).

Safety

Traffic incidents and accidents have happened to all container ships, including large advanced ones. Incidents and accidents usually refer to fatalities during particular stages of operations such as loading and unloading at the port terminals, operations in

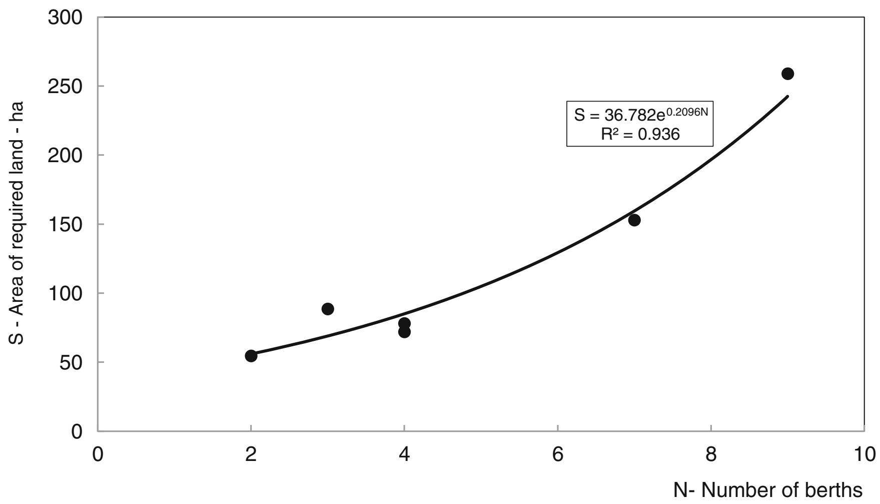


Fig. 4.22 Relationship between the area of land occupied by U.S. port container terminals and the number of berths (CGI 2007)

ports, restricted and coastal waters, and open sea transit. Similarly as in other transport modes, the risk of loss of life is expressed by the number per unit of output. In addition, the impacts of incidents and accidents on the environment are taken into account. They are usually expressed in absolute terms. For example, some figures indicate that the average number of fatalities was 3.52×10^{-3} fatalities/ship-year, the number of environment-pollution events 4.36/year, and the average number of lost containers 182/year, all over the 1993–2004 period (IMO 2007).

In order to assess the risk of potential fatalities in container ship crew members, the main factors of risk include collisions, contact, grounding, fire/explosion, and heavy weather. Respecting this classification, the risk of potential fatalities among ship crew members has been assessed as 9.00×10^{-3}, and that for an individual crew member as 2.25×10^{-4}. The latter is lower than the maximum perceivable risk for a crew member of 10^{-3}, but higher than the "negligible" risk of 10^{-6}. At the same time, the perceived environmental risk causing release of substantial quantities of dangerous substances and fuel has been estimated to be 1.01 (IMO 2007). This implies that large advanced container ships are at least as safe as their smaller counterparts.

4.3.3 Evaluation

Large advanced container ships possess both advantages (Strengths and Opportunities) and disadvantages (Weaknesses and Threats) as compared to their smaller counterparts.

Advantages

- Strongly supporting international trade, thus contributing to further globalization of the national and global economies;
- Supplying relatively substantial transport capacity per service, which in turn can compensate the diminishing technical productivity during slow steaming;
- Slow steaming can improve the economic performances by reducing the operating costs and the environmental performance by improving energy efficiency, i.e., reducing fuel consumption and related emissions of GHG (CO_2); in addition, slow steaming can contribute to increasing the number of transport units/ships in operation serving given volumes of demand and consequently partially compensate short-term capacity oversupply caused by market volatility; and
- Large advanced container ships are convenient in terms of technical/technological feasibility and testing and implementing different alternative technical/technological and operational innovations for improving technical/technological, operational, economic, and environmental performances (particularly energy efficiency).

Disadvantages

- Calling or serving, i.e., being able to access, a limited number of ports due to limitations of the maximum draught, and efficient and effective maneuverability;
- Requiring substantial investments in some port/terminal infrastructure, facilities, and equipment (berths, cranes, store areas for containers, etc.) for efficient and effective handling;
- Requiring increasing use of coastal land for building larger berths, terminals, and inland transport infrastructure;
- Vulnerability to market volatility easily creating imbalances between demand and capacity, thus compromising the overall economic feasibility; adapting to such conditions requires modification of the service network(s) into stronger hub-and-spoke configuration(s) with a smaller number of ports serving mature markets with relatively stable freight demand in both directions;
- Economies of scale disappear rapidly beyond a certain size, i.e., over 10,000 TEU;
- Contributing to a decrease in the overall speed of supply chains and prolonging the period freight/goods remain within the chains, thus causing raising inventory costs due to slow steaming (Chap. 3);
- Remaining concerns relating to energy efficiency in terms of the current and prospective contribution to total fuel consumption and related emissions of GHG (CO_2) despite forthcoming technical/technological (EEDI) and operational (SEEMP) improvements, at least until HFO is mainly used; and
- Some reservations including criticism as to whether it is correct to use EEDI for assessing energy efficiency, implying the need for further modifications and improvements.

Finally, regardless of the above-mentioned advantages and disadvantages, the fleet of large advanced container ships will likely continue to grow, while being

continuously modernized by simultaneously improving their technical/technological, operational, economic, and environmental performances. In combination with their size, these have already and will continue to make such ships advanced.

4.4 Liquid Hydrogen-Fuelled Commercial Air Transportation

1957	The first successful test of the bomber aircraft B57 modified to use LH_2 (Liquid Hydrogen) under military auspices (U.S.)
1988	The first flight of the TY155 aircraft with modified Engine No.3 by *Kuznetsov* to use LH_2 or NG (Natural Gas) (USSR)
1990	The standard reference book "*Hydrogen Aircraft Technology*" is published by D. Brewer (U.S.)
1990s	The European–Canadian "*Euro-Quebec Hydro-Hydrogen Pilot Project*" covers many aspects of hydrogen use (Europe, Canada)
2003	The study carried out in the scope of the 5th EC FMP (Framework Program) covers different aspects of making the transition from conventional to LH_2 fuel such as: aircraft configuration, systems and components, propulsion, safety, environmental compatibility, fuel sources and infrastructure, and transition processes, from both global and regional perspective (Europe)

4.4.1 Definition, Development, and Use

Mitigating the medium- to long-term impacts of the APT (Air Passenger Transport) system on the environment in terms of energy consumption and related emissions of GHG (Green House Gases) and society can be achieved, among other endeavors, also by further development of aircraft propulsion systems (engines) as follows:

- Improving existing turbofans in combination with using fuels synthesized from alternative sources such as coal and natural gas, and biomass from plants and algae; these engines are expected to be generally more fuel efficient by about 15 % and quitter by about 25 dB; and
- Improving existing turbofans by using advanced materials enabling adapting combustion thanks to higher combustion temperatures, including developing advanced concepts such as the following:
  - Ultrahigh by-pass ratio engines (Geared turbofan (GTF)) developed by Pratt and Whitney and NASA (National Aeronautics and Space Administration) in the U.S., which would be about 15 % more fuel efficient and 30 dB quitter as compared to existing turbofans;

– Open-rotor engine (GTF) or Unducted Fan (UDF) developed by GE (General Electric) and NASA, which would be about 25 % more fuel efficient and 15–20 dB quitter then their existing counterparts;
– Hybrid and electric engines such as Boeing/NASA SUGAR Volt-hybrid and Voltair (all-electric aircraft concept), which would require major advances in the battery energy density such as the Lit-Air (Lithium Air) battery concept; the theoretical energy density of this concept is about 11.5 kWh/kg, which is close to that of gasoline/kerosene of about 13 kWh/kg; and
– Improvements and modification of existing turbofan engines enabling them to use LH_2 (Liquid Hydrogen) as fuel.

The latest concept as an alternative for mitigating the global emissions of GHG by APT over the future long-term period implies switching from conventional jet fuels (kerosene) to alternative fuels, one of which is LH_2 (Liquid Hydrogen) (Janic 2008, 2010).

4.4.2 Analysis and Modeling Performance

4.4.2.1 Liquid Hydrogen (LH_2) as Fuel

Manufacturing, logistics, and economics

Some of the methods for manufacturing hydrogen as a fuel are already commercially available, but the produced quantities are used only in small niche markets as a chemical substance and not as an energy commodity. For commercial use in general, hydrogen can be produced from chemically reformed natural gas, fossil fuels, and/or biomass feedstock using conventional chemical processes. In addition, it can also be produced by using electricity or heat, sunlight, and/or specialized microorganisms for dissociating water. In cases of producing relatively large quantities, the process will be mainly driven by economic reasons including the full logistics costs (Chevron 2006; IEA 2006).

The logistics of hydrogen includes its transport and storage. Hydrogen can be transported and stored after being converted into a highly concentrated form either by increasing the pressure or by lowering the temperature. In general, over shorter distances, it is transported as a compressed gas by dedicated vehicles and/or pipeline systems. Over longer distances, it is exclusively transported as a liquid by dedicated vehicles operated by all transport modes. It is stored in high-pressure cylindrical tanks and containers (IEA 2006).

The economics of hydrogen implies the amount of energy consumed for its production, packaging, transport, and storage, all depending on whether it is a liquid or gas. For example, the energy input could be about 2.12 and 1.65 times higher than the energy content of the delivered liquid and gas hydrogen, respectively (i.e., loss factor). In both cases, the loss factor is considerably higher than that of

conventional jet fuels (about 1.12) (Bossel and Eliasson 2003). In addition, the most important issue in supplying hydrogen as an energy commodity is a competitive price. This depends greatly on the primary sources and the related manufacturing processes on the one hand, and some market mechanisms such as, for example, taxes on the emissions of CO_2 (Carbon Dioxide), on the other. The price of hydrogen should in general be comparable to that of conventional jet fuel. In this context, in the long term the prices of conventional jet fuel are expected to increase and that of hydrogen to decrease, which makes the expectation of comparable prices for both fuels more realistic. Some estimates indicate that in 2035, the production costs of hydrogen will range between 0.8 and 3.5 $US/kg H_2 (IEA 2006).

Operational and environmental performances

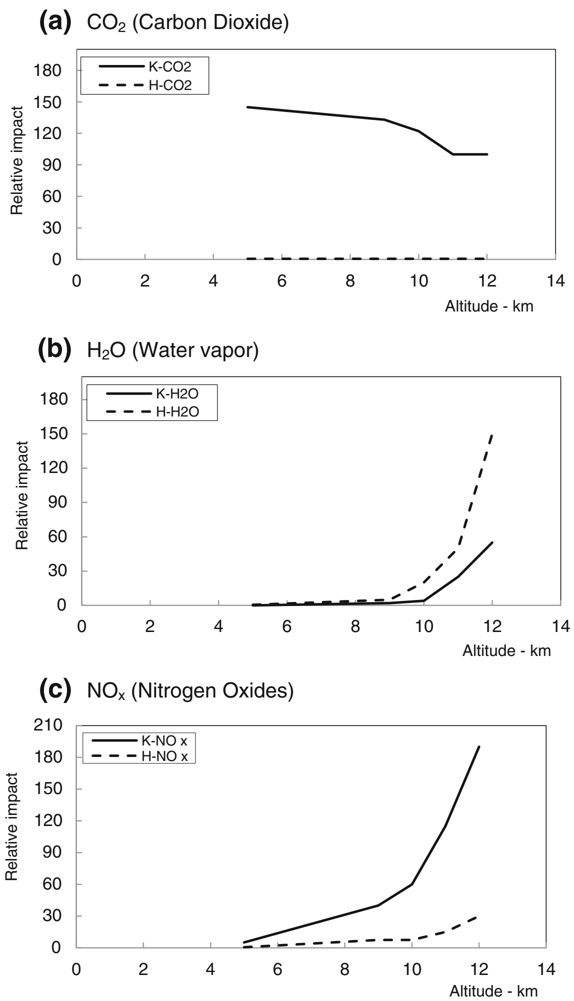
Hydrogen as a fuel for APT is going to be in the liquid aggregate state (i.e., LH_2—Liquid Hydrogen). Its main operational characteristics include its specific energy (120 MJ/kg), specific density (0.071 kg/m^3 at 15 °C), energy density (8.4 MJ/l), and boiling point (−253 °C) (Chevron 2006; Daggett et al. 2006). As compared to conventional jet fuel, LH_2 has the following advantages in terms of emissions of particular GHG: 0 versus 0.50 g CO; 0 versus 0.75 kg CO_2; 0.78 versus 0.30 kg H_2O; 0.02–0.102 versus 0.41 g NO_x; and 0 versus 0.20 g UHC (this is based on 10 MJ of energy content obtained from 0.5 l of LH_2 and 0.3 l of Jet A) (Daggett et al. 2006; EEC 2005). Thus, its burning does not produce CO_2 or SO_x. Increased emissions of H_2O and NO_x (the latter under specific conditions) remain the only matter of concern. Figure 4.23a, b and c shows the net relative impact of GHG from conventional jet fuel/kerosene (K) and LH_2 (H) on global warming.

In general, the net impact of GHG such as H_2O and NO_x on global warming increases more than proportionally, and that of CO_2 decreases less than proportionally as the aircraft flying altitude increases. In the case of kerosene, increasing the flying/cruising altitude from 9 to 11 km increases the net impact of NO_x by about a half and that of H_2O by about 75 %, the latter due to the formation of contrails since the aircraft fly in the troposphere. At the same time, the impact of CO_2 decreases by about 30 %. In the case of LH_2, increasing the flying/cruising altitude from 9 to 11 km increases the impact of NO_x up to about 10 % and that of H_2O by about 50 %. There is no CO_2 impact.

Social/policy performances

The main social/policy performances of LH_2 are considered to be safety, i.e., not causing incidents/accidents resulting in injuries, loss of life, or damaging properties due to known reasons. In general, LH_2 can be a safe fuel. Nevertheless, its main potential disadvantages are its explosive rate of 13–79 % concentration in the air and its very low ignition energy (about only 0.02 mj). LH_2 also mixes faster with air than jet fuel vapor, and disperses rapidly through the air in contrast to jet fuel, which pools on the ground. It burns with a nearly invisible, colorless, and odorless flame, which is also an important safety concern (IEA 2006).

Fig. 4.23 Impacts of GHG (Green House Gases) from conventional jet fuel (kerosene) and LH_2 (Liquid Hydrogen) on global warming depending on the aircraft flying altitude (Penner 1999)



4.4.2.2 The LH_2-Fuelled Commercial Aircraft

Development

Research on using hydrogen for commercial aircraft has been carried out in Europe, the U.S., and the Russian Federation for a considerable length of time. However, the first ideas and related experiments emerged more than 70 years ago and continue until nowadays. Recently, different projects have provided a vision of the prospective technical/technological, operational, economic, environmental,

and social/safety performances of cryogenic aircraft expected to be fully developed by around 2020 and consequently commercialized by around 2040 (EC 2003; EEC 2005).

Technical/technological and operational performances

In light of the characteristics of LH_2 as compared to conventional jet fuel (2.8 higher specific energy and about 11 times less specific density), LH_2 fuelled or cryogenic aircraft will require about 4.3 times more fuel volume for equivalent energy output than conventional aircraft. Therefore, their main design characteristic will be a relatively large volume of well-insulated cylindrical fuel tanks. They can have different positions within the aircraft configuration: above the payload (passengers and freight), above and aft of the payload, and fore and aft of the payload section. The wings could, with no fuel storage space, be smaller. The results will be increased aerodynamic resistance and aircraft empty weight as compared to conventional aircraft. However, the much lower weight of LH_2 is expected to compensate for such an increase in the empty weight and consequently contribute to reducing the maximum take-off weight (Brewer 1991; EC 2003).

Cryogenic jet engines will retain the basic structure of conventional jet engines but with some necessary modifications, such as fuel pumps, fuel control unit, and combustion chambers. Experiments so far have shown that these engines will have about 64 % lower Specific Fuel Consumption (SFC) than conventional jet engines (0.0976 vs. 0.2710 (kg/h)/kg for cruising and 0.0512 vs. 0.1420 (kg/h)/kg for the take-off phase of flight). In addition, they are expected to be 1–5 % more efficient in generating thrust from the given energy content. For Supersonic Transport Aircraft (STA), the specific consumption of LH_2 and Jet A fuel during cruising is expected to be about 0.260 (kg/h)/kg and 0.680 (kg/h)/kg, respectively, (the ratio for Jet A/LH_2 is 2.61). Last but not least, the hydrogen engines for either aircraft category are expected to operate with a slightly lower turbine entry temperature, which in turn will extend their life and reduce maintenance costs (Brewer 1991; Corchero and Montanes 2005; EC 2003; Guynn and Olson 2002; Svensson et al. 2004; http://www.tupolev.ru).

Economic performances

Over the 2003–2007 period, the share of fuel cost in the total operating costs of commercial airlines stood at about 30 % (EC 2003). Respecting the unit price of LH_2, the latest price of conventional jet fuel, and the lower Specific Fuel Consumption of cryogenic engines of about 64 % (i.e., 1 kg Jet A is equivalent to 0.36 kg LH_2), estimates show that the share of fuel costs in the total operating costs of cryogenic aircraft could vary between 45 % (1$US/kg LH_2) and 78 % (1.73$US/kg LH_2), if the prices of other inputs are assumed constant. Equalizing the prices of both fuels to 1$US/kg, the shares of corresponding costs would amount to about 60 and 35 %, respectively, mainly due to the lower Specific Fuel

Consumption of cryogenic aircraft. This scenario appears realistic since the prices of conventional jet fuel are expected to continue to rise, while those of LH_2 are assumed to decrease as both the efficiency of production and the overall logistics improve.

Environmental performances

Cryogenic aircraft powered by LH_2 do not emit CO_2. However, water vapor (H_2O) emitted in quantities about 2.6 times higher than by conventional aircraft at and above cruising altitudes of 31,000 feet (FL310; FL-Flight Level) will be the main GHG. However, its impact as compared to that of conventional aircraft appear to be much lower (Marquart et al. 2005). Reducing the cruising altitude is an option for eliminating these impacts. However, this could compromise other performances. In addition, cryogenic aircraft are assumed to emit about 5–25 % less NO_x than their conventional counterparts, which is expected to be achieved through the design of the combustion chamber of cryogenic engines (EC, 2003). Table 4.6 gives the environmental performances of typical long-range conventional and cryogenic aircraft in relative terms, mainly for comparative purposes.

Social/policy performances

As with fuel, the main social performance of cryogenic aircraft should be safety. As applies to fuel in general, cryogenic aircraft should be at least as safe as their conventionally fueled counterparts. In the event of an accident, LH_2 burns much faster (15–22 s) with low heat radiation, thus mitigating the fire impact in cases of collapsing fuselage. This contrasts to the impact of fire from conventional jet fuel. In addition, burning LH_2 covers a much smaller surface area (EC 2003). The overall safety figure also includes the appropriate design and operation of the airport fuel supply system. It seems likely that the manufacturing of LH_2 will take place at the airport fuel storage area that reserves will be stored in the large storage tanks, and that fuel will be usually delivered to the aircraft at the airport parking stands through a dedicated underground pipeline system.

Table 4.6 Environmental performances of typical long-range conventional and cryogenic aircraft—ratio (EC 2003; Janic 2008)

Characteristic	Conventional aircraft (Jet A)	Cryogenic aircraft (LH_2)
Fuel energy content	1	0.36
Volume of fuel	1	11
Volume of fuel tanks	1	4.3
MTOW	1	0.85–1.05
Aerodynamic resistance	1	1.1
Pollutants CO, CO_2, SO_x, HC	1	0
H_2O	1	2.6
NO_x	1	0.05–0.25

4.4.2.3 Modeling Performances of a LH_2-Fueled Air Transport System

Modeling the performances of a LH2-fuelled commercial air transportation includes the structure and application of the methodology. The former consists of the models for a single and two aircraft fuel technologies. The later embraces deriving the input data and analysis of results.

Structure of the methodology

LH_2-fueled APT is expected to be a "carbon-neutral" system. This implies that despite the continued growth of commercial air passenger transport demand over the future period of time, the energy/fuel consumption and related emissions of GHG of the APT system will remain constant or even decrease. The methodology for assessing such developments consists of the models for estimating the annual quantities of emissions of GHG by the APT system using: (i) one single (conventional), and (ii) two (conventional and cryogenic) aircraft fuel technologies, both on the global scale (Janic 2008).

The model for a single aircraft fuel technology

The global emissions of GHG generated by commercial air transportation in the given year of the observed period can be estimated as follows:

$$E_n = V_0 * (1 + i_v)^n * F_{C0} * \left(1 - i_f\right)^n * \sum_{l=1}^{L} e_l \tag{4.8a}$$

where

- E_n is the total emission of GHG in year (n) counted from the beginning of a given period of N years, i.e., the base year "0" (tons);
- V_0 is the volume of air traffic demand in the base year (*0*) of a given period (RPK—Equivalent Revenue Passenger Kilometers)[2];
- F_{C0} is the average consumption of conventional jet fuel in the base year (*0*) of a given period (g/RPK);
- i_v is the average annual rate of growth of traffic demand in terms of equivalent RPKs over a given period of time (%);
- i_f is the average annual rate of improvement of the average unit fuel consumption over a given period of time (%); and
- e_l is the emission rate of the l-th green house gas (g/g of Jet A fuel).

According to Eq. 4.8a, the total emissions E_n can be affected through the influencing variables in the given (target) year (n) as follows:

[2] Equivalent RPKs are regarded as the sum of RPKs and RTKs (Revenue Ton Kilometers) (1 RTK = 10 RPK).

- Achieving a rate of improvement of the average unit fuel consumption compared to the rates of air traffic growth, i.e., $i_f \geq i_v/(1 + i_v)$;
- Slowing air traffic growth according to the rate of improvement in the unit fuel consumption, i.e., $i_v \leq i_f/\left(1 - i_f\right)$;
- Constraining air traffic growth by imposing a cap on the total emissions of green house gases, i.e., $i_v = \left[E_n^*/\left[V_0 * F_{C0} * \left(1 - i_f\right)^n * \sum_{l=1}^{L} e_l\right]\right]^{1/n} - 1$, where E_n^* is the "cap" on the total emissions of green house gases in the target year (n); and
- Affecting the air traffic growth rate by weakening its relationship with the main internal and external demand-driving forces.

The first three above-mentioned conditions are not likely to be achieved before 2025/26 and beyond, mainly because of the relatively wide differences between the current and predicted average annual air traffic growth rates (3.1 %, IPCC 1999; 5.4 %, Airbus 2006; Boeing 2007) and the rates of improvement in fuel efficiency (1.2–2.2 %; EEC 2005; IPCC 1999; Learmount 2007; Lee et al. 2004). For example, in the first case i_f should be not less than 4.3–4.8 %, respectively, which is almost twice as much as the current very optimistic 2.2 %. In the second case, the air traffic growth rate i_v should not be greater than the expected rate of improvement in fuel efficiency, i.e., about 1.2–2.2 %. In the third case, the main problem appears to be criteria for setting up the annual cap E_n^* and its monitoring and control (IPCC 1999, 2001). The last case seems highly uncertain.

Consequently, the above-mentioned expected reductions in fuel consumption and related emissions of GHG by technological and operational improvements appears to be the only realistic but certainly insufficient alternative. This indicates that achieving a "carbon-neutral" air transport system will be extremely difficult if not impossible with conventional aircraft jet fuels.

The model for two aircraft fuel technologies

The introduction of cryogenic aircraft powered by LH_2 is expected to be a process of gradually replacing part of the conventional aircraft fleet. This process will be able to start if and after the following conditions are fulfilled:

- A pallet of different categories of cryogenic aircraft are fully developed regarding the size–range (small-short, medium–medium, large–long);
- The sufficient manufacturing capacities of cryogenic aircraft and LH_2 are available to satisfy the given rate of replacement;
- The airport infrastructure for supplying LH_2 is fully operational;
- The market prices of LH_2 are competitive to the prices of conventional jet fuel; and
- The emissions of GHG during the manufacture of LH_2 are captured and stored.

The gradual replacement process will take place over a "transitional" period during which both conventional and cryogenic aircraft will be used. The contribution of such a "hybrid" fleet to the total emissions of GHG in the year (k) of the "transitional" period of K years can be estimated, based on Eq. 4.8a, as follows (Janic 2008):

$$E_k = V_0 * (1 + i_v)^k * \left[F_{C01} * \left(1 - i_f\right)^k * (1 - ki_h) * \sum_{l=1}^{L} e_l + F_{C02} * (ki_h) * \sum_{m=1}^{M} e_m \right] \tag{4.8b}$$

where

i_h is the average share of the total volume of traffic (RPKs) carried out by cryogenic aircraft in each year of the observed period ($0 \leq ki_h \leq 1$; $k = 1,2, \ldots, K$);

F_{C01}, F_{C01} is the average unit fuel consumption of conventional (Jet A) and cryogen (LH_2) fuel, respectively, in the base year (0) of the given "transitional" period (g/RPK); and

e_m is the emission rate of the m-th GHG from cryogen fuel (LH_2) (g/g of JetA fuel).

The other symbols are analogous to those in Eq. 4.8a. The parameter F_{C01} in Eq. 4.8b is assumed to be at the level achieved when the process of introducing cryogenic aircraft starts, i.e., at the beginning of the "transitional" period, and will continue to improve over the said period. The parameter E_{C02} will be lower than E_{C01} approximately proportionally to the ratio between the specific energy of conventional jet fuel and LH_2, i.e., 43.2/120 = 0.36. This ratio is assumed to remain constant over the "transitional" period. The cryogenic aircraft replacing conventional aircraft will be introduced each year in constant proportions, thus implying their constantly increasing share in satisfying air traffic demand (RPKs). In this case, the eventual stabilization and/or even reduction in emissions of GHG in the given (target) year could be achieved by the same alternatives as in Eq. 4.8a. In addition, one additional alternative could consist of adjusting the rate of introducing cryogenic aircraft in Eq. 4.8b as follows:

$$i_h = \left[i_v * F_{C01} * \left(1 - i_f\right) * \sum_{l=1}^{L} e_l \right] / \left\{ \left[F_{C01} * \left(1 - i_f\right) * \sum_{l=1}^{L} e_l - F_{C02} * \sum_{m=1}^{M} e_m \right] * [1 + i_v(k+1)] \right\} \tag{4.8c}$$

where all symbols are as in previous equations.

Application of the methodology

Input

The methodology is applied to the long–term development of the APT system, related fuel consumption, and emissions of GHG. The time horizon is divided into

three subperiods: 2006–2025/26, 2025/26–2040, and 2040–2065. The first sub-period is specified by the two leading aircraft manufacturers (Airbus 2006; Boeing 2007). The second sub-period is specified as the period until the start of the "en-masse" introduction of cryogenic aircraft (2040). The last period represents the "transitional" period of gradually replacing a certain proportion of conventional aircraft with cryogenic aircraft. This implies that at the end of the final period, a "hybrid" aircraft fleet consisting of both aircraft categories will operate. The potential "what-if" scenarios of prospective development of APT demand and cryogenic aircraft over the specified periods of time are used as inputs for the methodology and are given in Table 4.7.

The growth rates of air traffic demand are assumed to be constant during each sub-period and to decrease when looking further into the future.[3] This reflects the increasing maturity of the air transport market combined with the weakening dependency of air transport demand and its main driving forces. The fuel efficiency of conventional aircraft is assumed to permanently improve over time, albeit at a decreasing rate. Aircraft utilization is assumed to generally increase over time at a decreasing rate, which implies the number of aircraft increasing at a decreasing rate. The rate of introduction of cryogenic aircraft is assumed to be constant in each year of the "transitional" period, thus providing the share of cryogenic aircraft in the total of RPKs of 22 and 50 % by the end of the year 2065.

Table 4.7 Scenarios of the future development of the APT demand and aircraft fleet (Janic 2008)

Input variable	Period		
	2006–2005	2026–2040	2040–2065
Basic annual traffic volume: V_0 (trillion Equivalent RPKs)	6.26[a]	13.78	22.61
Average traffic growth rate: i_v (%)	5.4[a]	3.5	2.0
The number of aircraft at the beginning of the period	18230[a]	36420	48823
Average aircraft utilization at the beginning of the period (trillion RPK/year)	0.3615	0.3784	0.4632
Rate of improvement of aircraft utilization: (%/year)	1.50	1.25	1.00
Average unit fuel consumption of conventional aircraft: E_{C01} (g/RPK)	27.7	19.66	16.28
Rate of improvement in E_{C01}: i_f^- (%/yr)	1.70	1.25	1.00
Average unit fuel consumption of cryogenic aircraft: E_{C02} (g/RPK)	N/A	N/A	5.86
Average share of the total traffic carried out by cryogenic aircraft: i_h (%/yr)	0.00	0.00	1.00/2.00

[a] Airbus 2006; Boeing 2007
[b] $E_{C02} = 0.36\ E_{C01}$; *N/A* Not Applicable

[3] The average growth rate of APT demand over the entire time horizon is about 3.2 %, which is similar to the growth rate of 3.1 % over the 1990–2050 period in one of the scenarios of the air traffic growth developed by IPCCs. This rate produces a total of about 16.5 trillion RPKs in 2050 and 26.02 trillion RTKs in 2065 (IPCC 1999).

The eventual improvements in the unit fuel consumption of cryogenic aircraft are not considered due to the lack of realistic data.

Results

The results from application of the methodology using the above-mentioned inputs in Table 4.7 are shown in Fig. 4.24a, b, c. It shows the development of APT demand and related emissions of GHG (CO_2, H_2O, and NO_x, respectively) over time in relative terms (Index).

Figure 4.24a shows that if only conventional aircraft continue to be used, the future emissions of CO_2 will continue to increase driven by increasing volumes of air traffic. However, the emissions of CO_2 will rise more slowly than the traffic, mainly due to permanent improvements in aircraft fuel efficiency on the one hand, and aircraft utilization on the other. For example, at the end of the period (2065), air traffic will have increased six fold and the related emissions of CO_2 by 3.5 times as compared to those in the base year (2006). This is lower than in the IPCC's Reference Scenario where the CO_2 emissions in 2050 are predicted to be about 3.9 times greater than in 2006 (IPCC 1999). Consequently, it becomes evident that independently of the rate of improvement of conventional aircraft, stabilization of the annual global emissions of CO_2 will not be possible under conditions of unconstrained growth of air traffic demand implying that achieving a "carbon neutral" system will not be possible. However, from the time of introducing cryogenic aircraft even at a modest proportion of only about 1 % per year, the emissions of CO_2 will start to gradually slow down, stagnate, and finally stabilize by 2065 at a level about 2.8 times higher than in 2006, despite continuous traffic growth. If the rate of introduction of cryogenic aircraft is about 2 % per year, the rate of CO_2 will immediately start to decrease and be about 1.8 times higher in 2065 as compared to the base year (2006). This indicates that cryogenic aircraft may enable the decoupling of growth of air traffic and related emissions of CO_2 and thus contribute to achieving a "carbon neutral" APT system.

Figure 4.24b shows that emissions of H_2O will continue to increase in line with air traffic demand independently of the aircraft technology. If only conventional aircraft are used, the level of H_2O in 2065 will be about 3.3 times greater than in the base year (2006). At the same time, air traffic demand will be about 7 times higher. This indicates that, as in the case of CO_2, improving the aircraft fuel efficiency and daily utilization will slow down the increase in H_2O emissions. Introducing a relatively low proportion (1 %) of cryogenic aircraft will slightly (negligibly) increase this level during the period of replacement (2040–2065). However, if the proportion of introduced cryogenic aircraft is 2 %, the level of H_2O in 2065 will be about 4.2 times higher than in the base year (2006). These figures confirm the present concern that cryogenic aircraft will not stabilize emissions of H_2O, but, to the contrary, contribute to their substantial rise and thus the increased risk of more intensive formation of contrails.

Figure 4.24c shows the prospective long-term emissions of NO_x. As can be seen, similarly as in the case of the other two green house gases, when conventional

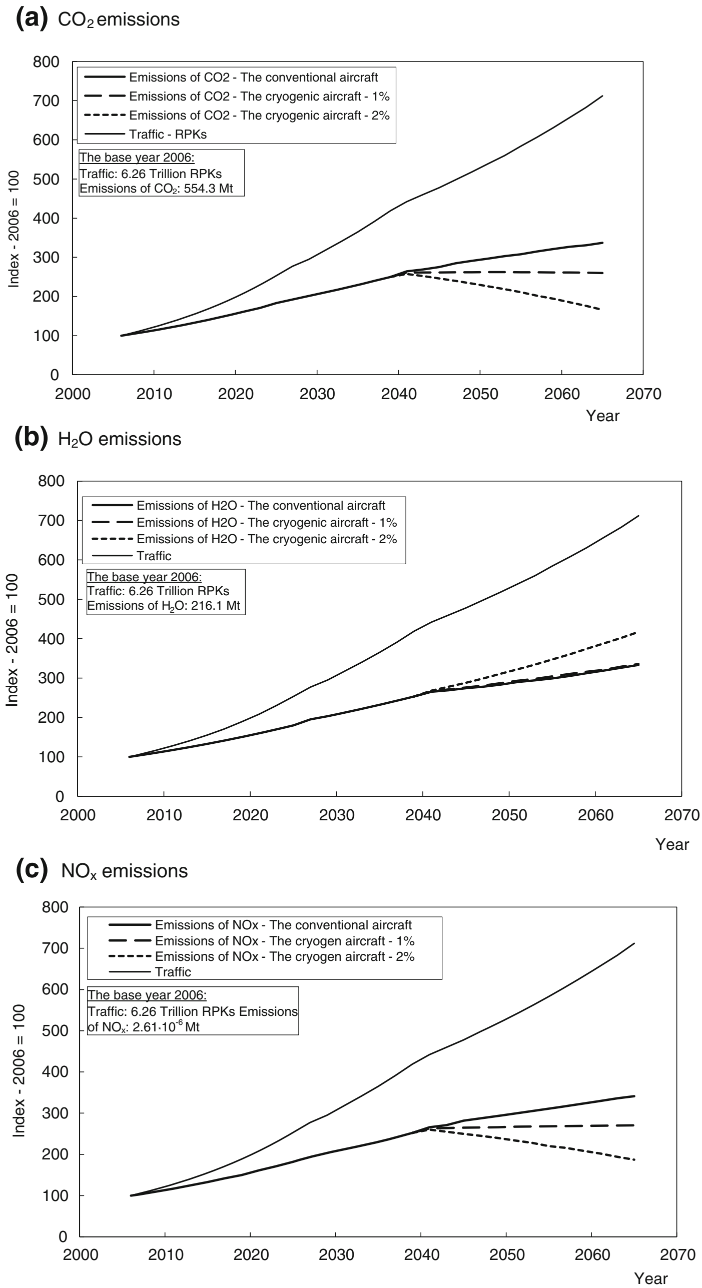


Fig. 4.24 Influence of cryogenic aircraft on the long-term global emissions of GHG (Janic 2008)

aircraft are exclusively used over the entire period (2006–2065), emissions of NO_x will continue to rise driven by the growth of air traffic demand, but again at a slower rate, mainly thanks to improvements in aircraft fuel efficiency and daily utilization. This again indicates that conventional aircraft will not be able to stabilize the level of NO_x and thus make the system "carbon-neutral" under conditions of unconstrained air traffic growth. For example, the level of NO_x in 2065 will be about 3.5 times greater than that in the base year (2006), driven by an increase in air traffic demand by about 7 times. If cryogenic aircraft really achieve NO_x emission rates of about 5–25 % of that of conventional aircraft, their gradual introduction will certainly stabilize and even decrease the total emissions of NO_x despite growing air traffic demand. For example, if the rate of introduction of cryogenic aircraft is 1 %, emissions of NO_x in 2065 will stabilize at a level about 2.8 times higher than that in the base year (2006). If the rate of introducing cryogenic aircraft is 2 %, the emissions of NO_x will decrease by 2065 to a level of about 2 times higher than in the base year (2006).

4.4.3 Evaluation

The LH_2 (Liquid Hydrogen)-fueled APT (Air Passenger Transport) system possesses both advantages (Strengths and Opportunities) and disadvantages (Weaknesses and Threats) as compared to its conventional crude oil-based jet fuel/kerosene counterpart. In general, the advantages and disadvantages relate to LH_2 as a fuel and the aircraft/engine technology, as well as general environmental effects/impact.

Advantages

- The production cost of LH_2 can be comparable to those of conventional fuels by using primary sources such as solar, wind, and hydro energy, and SRM (Steam Methane Reforming) biofuels and biomass fuels;
- LH_2 aircraft engines are slightly more fuel efficient than their conventional crude oil-based counterparts;
- The life and related maintenance costs of LH_2 aircraft engines can be extended thanks to LH_2 fuel burning at slightly lover turbine temperatures;
- Using LH_2 in a wide range of margins enables reduction of NO_x emissions due to its burning characteristics;
- Using LH_2 definitely has a potential for mitigating, stabilizing, and even decreasing the cumulative emissions of GHG (Green House Gases) except H_2O (water vapor) in the future medium- to long-term period of time, despite continuous air traffic growth; this could be achieved by the gradual replacement of conventional aircraft by cryogenic (LH_2-fuelled) aircraft over the long-term future;
- The lower take-off weight and smaller engines of cryogenic aircraft make them less noisy than their conventional counterparts; and

- Increased use of LH_2 ensures national independence of fuel supply since LH_2 can, in contrast to crude oil, be produced in any country.

Disadvantages

- Increased emissions of H_2O remain a matter of concern;
- The benefits from savings in the emissions of GHG by using LH_2 only arise if the primary sources for its production are wind, solar, and hydro energy;
- LH_2 aircraft engines are just slightly more efficient than their conventional crude oil-based counterparts;
- A relatively substantial commercialization of LH_2-fuelled aircraft of a given category (long range in this case) is needed in order to produce the desired environmental effects;
- These long-range LH_2-fuelled aircraft would produce less relative savings in energy consumption compared to smaller short- and medium-range aircraft;
- LH_2-fuelled aircraft, related manufacturing plants for both vehicles and fuel, and the fuel supply infrastructure at airports do not exist yet and still need to be built; and
- Switching from conventional jet fuel to LH_2 seems, at least at present, to be technologically, economically, and environmentally rather risky; the latter in particular because the share of emissions of GHG by commercial air transportation in the total man-made emissions of GHG is expected to range between 3 and 5 % over the forthcoming medium- to long-term period of time.

Finally, it can be said that LH_2 (Liquid Hydrogen) and the related adaptation of vehicles/aircraft and logistics of fuel manufacturing, supply, and distribution at airports are the main characteristics that will enable further advances of the already advanced commercial air transport system.

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